Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM2009)

Evaluation of an Airborne Spacing Concept to Support Continuous Descent Arrival Operations

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***Abstract*— This paper describes a human-in-the-loop experiment of an airborne spacing concept designed to support Continuous Descent Arrival (CDA) operations. The use of CDAs with traditional air traffic control (ATC) techniques may actually reduce an airport's arrival throughput since ATC must provide more airspace around aircraft on CDAs due to the variances in the aircraft trajectories. The intent of airborne self-spacing, where ATC delegates the speed control to the aircraft, is to maintain or even enhance an airport's landing rate during CDA operations by precisely achieving the desired time interval between aircraft at the runway threshold. This paper describes the operational concept along with the supporting airborne spacing tool and the results of a piloted evaluation of this concept, with the focus of the evaluation on pilot acceptability of the concept during off-nominal events. The results of this evaluation show a pilot acceptance of this airborne spacing concept with little negative performance impact over conventional CDAs.**

Keywords- continuous descent arrivals; airborne spacing; merging and spacing

I. INTRODUCTION

The air transportation system currently faces two important challenges: reducing fuel consumption and environmental pollution generated by aircraft while increasing the capacity at high-density airports and the airspace surrounding them. During the past several years, increased interest in reducing airport community noise and the escalating cost of aviation fuel has led to the use of Continuous Descent Arrival (CDA) procedures to reduce noise, emissions, and fuel usage compared to current procedures. To provide these operational enhancements, arrival flight paths into terminal areas are planned around optimized vertical profiles. The profiles are designed to be near-idle descents from cruise altitude to the final approach fix (FAF) and are typically without any level segments. By staying higher and faster than conventional arrivals, CDAs also save flight time for the aircraft operator. The drawback is that the variation of optimized trajectories for different types and weights of aircraft requires the Air Navigation Service Provider to provide larger separation margins around an aircraft on a CDA than on a conventional arrival procedure. This additional space decreases the throughput rate of the destination airport. To maintain the arrival rates required for a very busy airport, different terminal area concepts have been evaluated, including: vectors and speed commands from a ground system [1], Required Time of Arrival procedures for CDAs [2], and speed commands generated on-board the aircraft [3-5]. In support of a government/industry partnership called Flight Deck-based Merging and Spacing (FDMS) led by the Federal Aviation Administration, this paper describes a human-in-the-loop evaluation of one of those airborne self-spacing concepts, the National Aeronautics and Space Administration's (NASA) Airborne Precision Spacing (APS).

APS is an operational concept where the control of the aircraft's speed is delegated by air traffic control (ATC) to the flight crew in order to precisely achieve an assigned inter-aircraft spacing. The concept allows the flight crew to make minor speed adjustments based on cues from an on-board system while flying a CDA and is intended to address both capacity and efficiency issues facing the air transportation system. The algorithm used for generating the speed commands has been under development for almost 20 years [6-10]. The current instantiation of this system, designed to support the FDMS effort, is called Airborne Spacing for Terminal Arrival Routes (ASTAR).

The focus of NASA's current airborne spacing concept is to develop and test an airborne self-spacing application that is compatible with CDAs [8-11]. In this concept, a ground-based automation tool would provide an arrival schedule and the related aircraft arrival sequence that would ultimately become ATC clearances for aircraft to perform self-spacing during CDAs. The clearance to the flight crew of the self-spacing aircraft, i.e., the ownship, would provide the flight identification of the aircraft they are to land behind and the inter-arrival spacing interval (in seconds). On-board equipment would then process data from automatic dependent surveillance-broadcast (ADS-B) messages from the lead aircraft. In addition to the basic ADS-B state data message, it is assumed that participating aircraft would also be transmitting the name of their arrival routing and their planned final approach speed via an ADS-B Operational Coordination Message [12]. The published routes would include altitude and speed constraints in addition to the lateral path and could include area navigation or standard terminal arrival routes with approach transitions that extend the arrival path to the runway. Prior to receiving ADS-B data from its lead aircraft, the ownship would simply fly the speeds assigned to the arrival route.

The results of numerous fast-time studies conducted by NASA on the operational procedures and associated algorithm have shown the potential viability of this concept [4, 5, 8, 13, 14]. However, several major questions still need to be addressed prior to operational use, including the evaluation of system usability and acceptability by the flight crew during off-nominal situations. This paper documents the results of a study aimed at addressing this latter subject. In this regard, a human-in-the-loop piloted evaluation was conducted to determine if the proposed FDMS procedures were acceptable and if the pilots were able to execute these procedures.

II. METHODOLOGY

A. *Experiment and Scenario Design*

The focus of this human-in-the-loop experiment was to examine off-nominal conditions, such as speed changes and vectors off the arrival route by ATC. The basic scenario for this test was designed to match the current flight-trials being used by UPS for CDA operations at the Louisville Standiford International Airport (SDF). Each test aircraft starts at a point prior to the top-of-descent (TOD) and flies a CDA to the Instrument Landing System (ILS) intercept for runway 17R at SDF. Two east-bound arrival streams were used, with the aircraft merging onto a single CDA prior to TOD. The CDA was based on the routes in use at SDF during 2007-2008 and included altitude and speed constraints. Each scenario consisted of eight aircraft, all piloted by subject pilots/crews, and was designed to provide a minimum of 5 nmi separation at the runway threshold. Seven of the eight aircraft simulations were flown by an individual pilot in a medium fidelity simulator. The eighth aircraft employed a full mission, high fidelity simulator with subject pilots operating as a two-person crew.

For this experiment, the first aircraft in every scenario used flight management system (FMS) guidance, including FMS speed guidance, to fly the aircraft from its starting position to ILS capture. Aircraft that were assigned a spacing instruction were expected to use the ASTAR-provided speed guidance whenever possible. The ASTAR speed guidance is designed such that the assigned spacing interval between the lead aircraft and the spacing aircraft will be achieved by the spacing aircraft at the runway threshold. The speed guidance was bounded to be within 10% of the published CDA speeds and to meet the 250 kt U.S. restriction below 10,000 ft mean sea level. All of the aircraft used ILS auto-land procedures to the runway threshold. The waypoint data for the CDA are shown in Table I.

TABLE I. WAYPOINT DATA

Waypoint	Significance	Distance to Go (nmi)	Published Constraints (speed / altitude)
ENL	Merge point	167	
PRINC	Near TOD	96	
CBSKT	TRACON[a] entry	43	240/11000
BRYDL		17	220/4300A
SLEWW	Turn to intercept final	12	180/4000A
SECRY	Turn to final	8.3	/3000
CHRCL	FAF	5.6	170/2350
RW17R	Runway threshold	0	

a. Terminal Radar Approach Control (TRACON)

The FDMS procedure required the pilots to enter the assigned leader's flight number and spacing interval on a special control display unit page. Forecast en-route and terminal area winds were entered into ASTAR via data-link. The ASTAR algorithm then calculated the Estimated Time of Arrival (ETA) for both aircraft to the runway threshold based on the CDA trajectory adjusted for winds. The assigned spacing interval was added to the lead aircraft's ETA and compared to the spacing aircraft's ETA. The algorithm then generated a speed command based on this time error comparison. If the lead aircraft's ADS-B data are initially unavailable, e.g., due to data-link range limitations, the speed guidance will operate in Profile mode, then automatically transition to Paired mode once the lead aircraft is within reception range. The ASTAR speed guidance was presented to the crew on the primary flight display. Because the FDMS concept is currently focused on a retrofit operation, the flight crew then used "speed intervention" and overrode the FMS speed guidance by entering the ASTAR speed via the mode control panel speed window. After crossing the FAF, the ASTAR speed guidance displayed the planned final approach speed. Autopilot and auto-throttle were used by all aircraft in this test.

For all spacing aircraft, the spacing instruction was to achieve a spacing of 150 s at the runway threshold. From an operational standpoint, it is important to note that while an aircraft is delegated the spacing responsibility, aircraft separation (beyond "see and avoid") in the FDMS concept remains an ATC responsibility. Aircraft in the arrival stream that did not have spacing assignments were initially placed 300 s behind the preceding aircraft and used FMS guidance. All aircraft were started at altitudes between flight level (FL) 330 [1] and FL370 and cruise speeds of 0.80 or 0.82 Mach. The starting position for the first aircraft was approximately 20 nmi before TOD. The starting positions for all the other aircraft were then adjusted to account for realistic delivery uncertainty,

[1] Each FL is stated in three digits that represent hundreds of ft. For example, FL 330 represents a barometric altimeter indication of 33,000 ft.

a normal distribution with 0 mean (*M*) and 30 s standard deviation (*SD*). The environment included a truth wind that was spatially homogeneous except for an altitude variation ranging from 10 kt / 242° at 30 ft above ground level to 90 kt / 250° at 45,000 ft. The wind was based on representative wind conditions at SDF. The wind forecast provided to the scheduling tool and the aircraft's FMS was intentionally set to an error of half the magnitude of the wind speed with a 20° clock-wise rotation error. All aircraft were modeled as the same type: heavy, two-engine, narrow-body transport aircraft, although with different initial gross weights. This weight difference caused a range of final approach speeds for the aircraft.

Each eight aircraft scenario included three off-nominal events. For one event, an aircraft was vectored approximately 5 nmi off-path during the initial descent then returned to the published arrival prior to terminal radar approach control entry. The off-path vector caused suspension of spacing guidance during the maneuver. The pilot could attempt to reengage the spacing tool once reestablished on the arrival. The second event involved the aircraft that was following the aircraft vectored in the first event. This following aircraft also needed to suspend spacing guidance because the algorithm does not provide a spacing command when the lead aircraft is not following a published route. Once the lead aircraft returned to the arrival path, the crew in the trailing aircraft could attempt to reengage the spacing tool. The third event consisted of either an ATC speed intervention occurring between FL180 and 12,000 ft or an excessive initial spacing error. For the speed intervention situation, the pilot procedure was to suspend spacing guidance until cleared by ATC to continue the arrival with speed at pilot's discretion. To protect against an excessive spacing error - one that would make it unlikely that the spacing goal could be achieved - a feasibility check was added to the spacing tool. If the spacing deviation, which was the absolute difference between the assigned spacing interval and the current prediction, was too large, the crew was alerted and instructed to terminate spacing and continue the arrival as a normal FMS-guided CDA.

The eight experiment scenarios showing what conditions were presented along with the aircraft assigned to that condition are shown in Table II. Each aircraft (AC) experienced one run as the lead (FMS guidance), one vector event, one lead off path event and either a speed or excessive initial spacing error event. Prior fast-time simulations have shown that while the spacing tool is designed to stabilize the aircraft arrival stream, disruptions are typically not "smoothed out" until the fourth aircraft after the disruption. With the scenario design of Table II, 85% of the spacing aircraft would be involved in a less-than-optimum spacing situation.

Three experiment sessions replicated the scenario design of Table II. Each session was conducted over a three day period, with the first day devoted to training for the subject pilots and a practice FDMS flight. The second day began with a second practice FDMS flight, and then five data collection flights were conducted, each lasting approximately 45 minutes. The third day began with the remaining three data collection flights, followed by a final questionnaire and an open forum debriefing session.

TABLE II. SCENARIO DESIGN

Arrival Sequence Number	Run 1	AC	Run 2	AC	Run 3	AC	Run 4	AC	Run 5	AC	Run 6	AC	Run 7	AC	Run 8	AC
1	FMS	1	FMS	4	FMS	8	FMS	7	FMS	2	FMS	3	FMS	6	FMS	5
2	Speed	2		6		4	Speed	1	Vector	8	Vector	4		3		1
3		6		8		3		3	Lead	1	Lead	5	Vector	7	Speed	8
4	Vector	5	Vector	1		1		5		7		8	Lead	8		4
5	Lead	3	Lead	2		5		3		4		6		5		7
6	FMS	7	Init	5	Init	6	FMS	8	Init	3	FMS	1	Init	4	FMS	2
7		4		7	Vector	2	Vector	6		6	Speed	7		3	Vector	3
8		8		3	Lead	7	Lead	4		5		2		1	Lead	6

Table definitions: FMS - not spacing. Vector - vectored during its initial descent. Lead - leading aircraft vectored. Speed - ATC speed instruction during initial descent. Init - excessive initial spacing error. All other aircraft (AC) received nominal spacing instructions. Note that AC 8 is always the full-mission simulator.

B. *Subject Pilots*

Participants consisted of 26 commercial airline pilots employed by major U.S. air carriers. Twenty-five males and one female age 38-60 years served as subject pilots. Ten of the participants were captains, and the other 16 were first officers. On average, the pilots had 18 years of airline experience and over 10,000 hours of airline flying experience. At the time of the study, 16 of the participants served as Boeing 777 pilots; seven served as 757/767 pilots; two served as 747 pilots; and one served as a 737 pilot. Twenty pilots having recent experience flying 747 and/or 777 aircraft were selected to fly as individual pilots using a medium fidelity simulator since their experience with glass cockpit technology facilitated their training and use of this simulator[2]. Six current 757/767 pilots flew as two-person crews in the NASA Langley Research Center Integration Flight Deck (IFD) since their knowledge base and experience facilitated their training and use of this high fidelity simulator.

[2] Twenty-one pilots were invited to fly medium fidelity simulators, but a last-minute subject pilot cancellation resulted in the use of a confederate pilot substitute. Data obtained from the substitute pilot were not included in the data analyses.

C. Facilities

1) Air Traffic Operations Laboratory: This experiment used the Air Traffic Operations Laboratory that includes a network of aircraft simulators [15]. The simulation platform, known as the Airspace and Traffic Operations Simulation (ATOS), can be used for batch Monte Carlo studies as well as real-time human-in-the-loop experiments. The ATOS is comprised of hundreds of real-time, high-fidelity aircraft simulators, of which 20 are also equipped with experimental cockpit displays and pilot interfaces. Each aircraft simulator is referred to as an Aircraft Simulation for Traffic Operations Research (ASTOR) station. Each ASTOR station is a medium fidelity aircraft and avionics simulation with low fidelity single-pilot interfaces [15]. The ASTOR models current aircraft components including: high-fidelity, six degrees of freedom equations of motion aircraft models, autopilot and auto-throttle systems, flight management computer, multi-function control display unit, mode control panel (MCP), and electronic flight instrumentation system control panel. The ADS-B model included high-fidelity transmission-reception and simulation of non-uniform Friendly Replies Uncoordinated in Time environment in the vicinity of the airport due to surrounding traffic and ground systems. The current experiment required the addition of a spacing algorithm and voice communication to the ASTOR models, as well as ATC controller stations using the Multi Aircraft Control System (MACS) developed at NASA Ames [16].

Three air traffic controllers used the MACS stations to provide a realistic traffic control environment for this experiment. The controllers also provided the vectoring and speed intervention instructions for the off-nominal events.

2) Integration Flight Deck (IFD): The IFD full-workload simulator is a replica of a large commercial transport category aircraft and is driven by an appropriate aircraft dynamics mathematical model [17]. The cockpit includes standard ship's instruments representative of a line operations aircraft, and the cockpit's visual system is a panorama system that provides 200° horizontal by 40° vertical field-of-view. The visual scene used for this experiment was the SDF terminal environment in a night-time setting.

D. Experiment Objectives

The first objective of this study was to assess pilot acceptability of the FDMS procedures during both nominal and off-nominal events. It was hypothesized that pilots would characterize their experiences with the proposed procedures as being positive when providing feedback via questionnaires and debriefing sessions. Furthermore, it was hypothesized that pilots would find the FDMS procedures to be complete and the workload level required to execute the procedures to be acceptable. With respect to subjective workload, pilots were expected to choose a rating of "3" or less when using the Modified Cooper-Harper (MCH) Rating Scale [18].

The second objective of this study was to determine if pilots were able to execute the FDMS procedures. It was hypothesized that pilots would avoid performing any objectionable aircraft maneuvers or operations, e.g., causing a violation of separation minima, and it was not anticipated that the study's confederate air traffic controllers would be required to provide any unwarranted or unscripted interventions as a result of the pilots' use of the proposed procedures.

The third objective of this study was to characterize system behavior and measure human and system performance in terms of aircraft spacing and stream stability. Specific hypotheses were not generated in conjunction with this research objective, but appropriate system performance metrics (outlined below) were used to analyze system costs and benefits and to assess operational performance requirements.

E. Dependent Measures

1) Subjective Assessments of the FDMS Procedures: Pilots' perceptions regarding the acceptability and completeness of the FDMS procedures were collected using post-scenario questionnaires, post-experiment questionnaires, and feedback obtained during post-experiment group debriefing sessions. Workload ratings were obtained using the MCH Rating Scale. Use of the MCH scale yields an overall workload rating ranging from "1" (indicating that the instructed task was very easy/highly desirable; operator mental effort was minimal; and desired performance was easily attainable) to "10" (indicating that the instructed task was impossible and could not be accomplished reliably).

2) Air Traffic Controller Intervention: Researcher notes and audio recordings of all verbal interactions taking place between the pilots and the air traffic controllers were used to identify unwarranted or unscripted controller interventions occurring as a result of the pilots' use of the FDMS procedures.

3) Objectionable Aircraft Maneuvers or Operations: Researcher judgment, video recordings of the IFD environment, simulation playback, pilot interaction data, e.g., button presses, and various aircraft state and trajectory data were used to determine if pilots accurately executed the proposed procedures.

4) System Performance Metrics: Data collected to characterize system behavior and measure human and system performance included inter-arrival spacing, number and location of speed changes, deviations from commanded aircraft speed and path, pilot conformance to speed guidance and implementation time, and various aircraft state and trajectory data.

III. Results and Discussion

Since the focus of this study was to determine if the proposed procedures were acceptable to the flight crews and if the pilots were able to execute these procedures, a significant portion of the results focuses on qualitative data obtained from pilot responses to questionnaires. Additional quantitative data are also presented relating to the ASTAR operational performance.

A. Acceptability of Procedures

An evaluation of the FDMS procedures' acceptability was obtained from the pilots via post-scenario and post-experiment questionnaires and post-experiment group debriefing sessions.

These data indicate that the pilots were comfortable with the FDMS procedures and that the proposed procedures would be acceptable and appropriate for use in the current flight deck environment. Using a scale of 1 ("very comfortable") to 7 ("very uncomfortable") to rate the use of the proposed spacing tool and procedures in flight, the pilots' mean response was 1.77 (*SD* = 0.91, *N* = 26[3]). Similarly, when asked to rate how well the spacing procedures and tool could be integrated into the current flight deck using a scale of 1 ("can easily be integrated") to 7 ("cannot be integrated"), the mean response was 2.31 (*SD* = 1.23, *N* = 26). After completing the eight flight scenarios, one pilot stated: "The procedure would have a good impact on not only fuel savings but also on standardization of approach and arrival procedures." This impression of the FMDS procedures was conveyed by a majority of the subject pilots.

The pilots expressed a relatively high level of confidence in the speed guidance provided by the spacing tool, and they indicated that it was relatively easy to follow the tool's speed guidance. The pilots provided a mean response of 1.81 (*SD* = 0.98, *N* = 26) when using a scale of 1 ("very confident") to 7 ("not at all confident") to rate the spacing tool's speed guidance, and they provided a mean response of 1.68 (*SD* = 1.01, *N* = 207[4]) when using a scale of 1 ("very easy") to 7 ("very difficult") to describe the level of difficulty associated with following the speed guidance. The pilots also used a scale of 1 ("very easy") to 7 ("very difficult") to indicate that it was relatively easy to maintain path (*M* = 1.79, *SD* = 1.00, *N* = 207) and speed (*M* = 1.73, *SD* = 0.93, *N* = 207) within the tolerances requested for this study (±400 ft and ±5 kt).

Pilots indicated that the spacing tool's speed guidance was acceptable during all flight segments and that the FDMS procedure has the potential to enhance safety. Using a scale of 1 ("very acceptable") to 7 ("very unacceptable"), the pilots provided the following ratings for the operational flight segments: cruise (*M* = 1.26, *SD* = 0.68, *N* = 207), descent to waypoint CBSKT, which had an 11,000 ft crossing altitude constraint, (*M* = 1.53, *SD* = 1.01, *N* = 207), between CBSKT and BRYDL, which had a 4,000 ft crossing altitude, (*M* = 1.69, *SD* = 0.96, *N* = 207), and between BRYDL and the runway threshold (*M* = 1.92, *SD* = 1.17, *N* = 207). When asked to assess the overall safety potential of the spacing procedure using a scale of 1 ("safety is enhanced") to 7 ("safety is compromised"), pilots provided a mean response of 2.58 (*SD* = 1.45, *N* = 26).

B. *Completeness of Procedures*

The completeness of the FDMS procedures was also evaluated (i.e., was there a procedure for all reasonably expected FDMS situations and was that procedure complete in addressing the situation?). When asked if they had been presented with "a complete set of procedures," 65% of the pilots answered in the positive. What is of interest in this result is that 15 of the 20 pilots flying the medium fidelity simulator (in a single pilot mode) stated that a complete set of procedures was defined in comparison with only 2 of the 6 pilots flying the high fidelity simulator (in a two-person crew mode). However, when asked if they had what they needed to perform the procedure, only one answered "no," with that pilot also flying the high fidelity simulator. When the pilots encountered off-nominal situations, they reported being able to follow the proposed procedures 88.3% of the time.

C. *Subjective Assessments of Workload*

Pilots used the MCH Rating Scale to provide a workload assessment after each simulated flight scenario. The pilots' mean MCH rating was 1.87 (*SD* = 0.78, *N* = 207), indicating that the task they were instructed to perform was easy/desirable; their mental effort was low; and desired performance was attainable. The pilots were not expected to select a rating higher than "3." However, the data reveal four instances of a rating of "4," indicating that the instructed task had a minor but annoying level of difficultly and required a moderately high level of mental effort to attain adequate system performance.

Of the 20 pilots that flew the medium fidelity simulator in a single pilot mode, 21.4% reported that the fact that they flew as a single pilot influenced their performance. Sixty percent of these same 20 pilots reported that the ASTOR station's PC interface and use of a mouse as a control mechanism influenced their ability to perform the instructed task. In comparison, 50% of the pilots flying the high fidelity simulator in a two-person crew mode reported experiencing anomalies or inconsistencies in the full-workload simulator that affected their ability to perform the instructed task. For example, one pilot reported that the use of a speed tape rather than an airspeed bug required him to alter his typical cockpit display scan pattern.

When asked if the FDMS procedures represent an acceptable workload trade-off compared with current day operations, e.g., ATC issuance of speed and heading changes, 25 of the 26 pilots responded in the positive. The majority of the pilots (92%) had no difficulty interfacing with the spacing tool, and 81% reported following the spacing tool's commands without error.

D. *Number and Location of Speed Changes*

It was assumed that the majority of the additional pilot workload from airborne spacing would come from the implementation of the commanded speeds changes, the latter being an artifact of not directly driving the autoflight with the ASTAR speed commands in this retrofit implementation. Implementing the commanded speed changes is a recurring task, the timing of which is often not predictable to the flight crew. Therefore, a design goal would be to find an acceptable compromise between fewer speed changes and higher spacing performance. The amount of crew workload or disruption created by a speed change is also dependent on what else the crew is doing at the time of the change. A speed adjustment while in level cruise would typically be associated with a much lower workload level than late in the arrival while trying to

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[3] A sample size, *N*, of 26 is associated with post-experiment questionnaire responses with each of the 26 pilots completing a post-experiment questionnaire.

[4] A sample size of 208 was anticipated since each of the 26 pilots was supposed to complete one post-scenario questionnaire after each of eight scenarios. However, one subject pilot did not complete one post-scenario questionnaire.

configure the aircraft to land. The total number of speed changes could also influence a pilot's perceived workload in conducting an FDMS operation.

This study's arrival procedure had five planned speed changes including the deceleration to the final approach speed. Not counting the Mach calibrated airspeed transition or the commanded speed when the spacing tool is started, the flight crews saw a median of six additional speed changes with an inter-quartile range, the central 50% of counts, from 4 to 7. The extreme values were 1 and 12. With flight times between 23 and 42 minutes, this resulted in an average of one change every five minutes with a maximum of one change every two minutes. Reference [19] states that speed changes of once per minute were acceptable to pilots.

Table III shows the location of the commanded speed changes partitioned by the operational flight segment. As expected, most of the speed changes occur late in the arrival. Prior to CBSKT, there was approximately one additional change due to spacing. In the final approach segment, there were almost three speed changes per arrival. It is noteworthy that at least one of these speed changes was caused by the design of the spacing tool, which would limit the commanded speeds based on the aircraft configuration. As an example, the profile calls for a deceleration from 220 kt to 180 kt. The crews would usually be at flaps one at 220 kt. The minimum speed at flaps one is approximately 189 kt. Therefore, the spacing tool would command 189 kt until the flight crew extended flaps five when the command would lower to 180 kt. There are an average of 1.3 speed changes per arrival that are an artifact of this configuration limiting.

TABLE III. COMMANDED SPEED CHANGES BY FLIGHT SEGMENT

Flight Segment	Speed Changes Per Aircraft	
	Published CDA	***Spacing generated***
Cruise	0	0.5
Initial descent	1	0.6
Terminal descent	1	1.4
Final approach intercept	1	0.6
Final approach	1	2.8
FAF to runway	1	0.1

E. *Performance*

1) Spacing at the Runway Threshold: The primary measure of performance for any air traffic spacing tool is the time or distance between successive arrivals at the point where the spacing is desired. Whereas some terminal-area spacing tools target the FAF for spacing, ASTAR uses arrival time estimates at the runway threshold as the basis for spacing. Since ASTAR does not command speed changes for spacing inside the FAF, it adjusts the spacing interval prior to the FAF to account for differences in final approach speeds to achieve the correct spacing at the runway threshold.

In this study, one of the results collected for analyses was the elapsed time between the lead and the spacing aircraft crossing the runway threshold (inter-arrival time) for each spacing pair. Of the 192 flights conducted for data collection, 156 were given spacing instructions. Twelve of the 156 were intentionally set up with large spacing errors behind their lead aircraft to evaluate procedures associated with excessive spacing errors. Of the 144 remaining cases, 19 were either not spacing at the end of their approach because of procedural FDMS termination, e.g., excessive spacing errors caused by speed or path deviations, or had simulator problems that invalidated the approach. Six of the spacing flights in the second experiment session were flown by a confederate pilot due to a last-minute subject pilot cancellation. The remaining 119 aircraft pairs were used for analyses of inter-arrival times and distances.

The distribution of inter-arrival times for the 119 spacing aircraft is shown in Fig. 1. The chart illustrates that two-thirds (66%) of the spacing aircraft achieved a spacing interval within 2.5 s of the assigned value of 150 s. Another 29% were between 2.5 and 7.5 s from the assigned value. Collectively, 95% of the spacing was within 7.5 s of the assigned value. This 95% value included aircraft that were part of the off-nominal events.

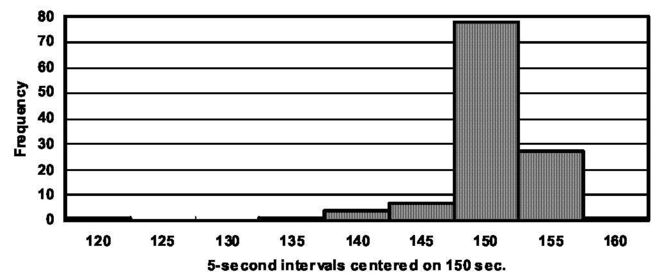

Figure 1. Distribution of runway threshold inter-arrival times.

Table IV shows the inter-arrival time statistics for all 192 flights used for data collection. The first two columns are the scripted conditions and the number of occurrences followed by the number of aircraft that completed the approach using FDMS procedures. Note that an aircraft following a speed interruption case is also grouped into the nominal classification. The means and medians of all conditions are clustered around the assigned spacing interval. The standard deviations are, in general, 5 s or less, with the exception of the aircraft that were following an aircraft that experienced an ATC speed interruption.

TABLE IV. INTER-ARRIVAL TIME STATISTICS

Conditions		***N***	***M***	***SD***	Median	Min	Max
Vectored	24	21	149.7	5.22	151.2	135.5	156.4
Lead vectored	24	11	151.5	2.37	151.6	148.5	156.6
Speed interruption	12	11	148.6	4.18	150.0	139.1	152.1
Following speed	12	11	148.6	9.63	150.2	120.5	157.0
Nominal	84	76	150.9	4.54	151.2	120.5	159.1
All	192	119	150.5	4.51	151.1	120.5	159.1

In terms of standard deviation, 61% of all cases were within 1 *SD* of the mean, and 92% were within 3 *SDs* of the mean. If an arbitrary standard of 5 s is used as the spacing standard, 85% of the spacing aircraft achieved that goal.

The one extreme value, 120.5 s, was the result of late flap deployment in configuring the aircraft for the approach. The published flap schedule was not observed and, apparently, the ASTAR speed limiting indicators on the displays were not recognized as action items. Flaps extension was delayed until the end of the turn to final approach, which necessitated rapid configuration changes to achieve a stabilized approach. It has not been determined if other factors related to single-pilot operation of the medium fidelity simulator were involved that may invalidate that particular approach.

Removal of the 120.5 s spacing set of performance data, i.e., data potentially due to pilot error, significantly reduces the affected inter-arrival time standard deviations as shown in Table V. For all aircraft, the 1 *SD* spread around the mean is 55%, and the 3 *SD* range is 89%. For completeness, a ±5 s range includes almost 86% of the cases.

TABLE V. INTER-ARRIVAL TIME STATISTICS EXCLUDING ONE OUTLIER

Scripted Conditions		*N*	*M*	*SD*	Median	Min	Max
Following speed	12	10	151.4	2.5	150.7	147.6	157.0
Nominal	84	75	151.3	2.9	151.2	141.3	159.1
All	192	118	150.8	3.6	151.2	135.5	159.1

2) Spacing at Arrival Waypoints: For a time-based spacing tool such as ASTAR, it is reasonable to assume the following performance of participating spacing aircraft along the arrival path:

- The distance between aircraft along the flight path will decrease between the merge point and the runway threshold.
- The time interval between participating aircraft crossing any point will be fairly consistent with the assigned separation interval at the threshold.
- Large excursions in ETAs at the threshold will result in more speed adjustments (in number and magnitude) than are nominally required to meet the published speed constraints.

For the first two assumptions, flight path distance-to-go and estimated and actual waypoint crossing time data were extracted for the 119 aircraft pairs that completed FDMS operations. One-hertz data were used in this analysis. The data were not interpolated for accuracy and therefore exhibit a latency of 0 to 1 s in waypoint crossing times. That resolution of up to two seconds in crossing time differences and the corresponding path-distance separations is acceptable for this discussion.

Tables VI-VIII are presented for the valid FDMS approaches. Waypoint data were not available for the cases that started inside the merge fix, had not rejoined the path before the lead crossed a waypoint, and for one threshold crossing in an otherwise nominal approach.

TABLE VI. PATH-DISTANCE SEPARATION WHEN LEAD AIRCRAFT CROSSES WAYPOINT

Waypoint	*N*	*M*	*SD*	Median	Min	Max
ENL	82	22.8	2.1	22.5	16.9	27.6
PRINC	119	21.9	1.9	21.9	16.9	26.3
CBSKT	119	16.2	1.5	16.1	12.5	20.7
BRYDL	119	12.3	0.7	12.3	10.8	13.9
SLEWW	119	11.4	0.6	11.4	10.2	13.0
SECRY	119	9.9	0.6	9.9	8.7	11.2
CHRCL	119	8.4	0.5	8.4	7.3	9.6
RW17R	119	5.7	0.2	5.7	4.7	6.1

The difference between estimated distance-to-go of the spacing aircraft and its lead exhibit a steady decrease in the means and standard deviations from the merge fix to the runway. There were no situations of concern by the ATC controllers for loss of separation.

TABLE VII. ESTIMATED TIME OF ARRIVAL DIFFERENCE WHEN LEAD AIRCRAFT CROSSES WAYPOINT

Waypoint	*N*	*M*	*SD*	Median	Min	Max
ENL	78	156.1	7.8	154.1	143.4	170.0
PRINC	119	149.3	7.6	149.7	131.6	165.8
CBSKT	108	151.3	11.9	149.3	117.8	190.2
BRYDL	119	154.1	7.5	153.6	134.6	172.6
SLEWW	119	156.7	6.8	156.4	141.7	173.1
SECRY	119	153.6	6.2	153.6	137.6	168.3
CHRCL	119	146.6	6.2	146.4	131.5	162.4
RW17R	118	146.3	4.2	146.6	123.6	157.2

TABLE VIII. ACTUAL SEPARATION TIME INTERVAL

Waypoint	*N*	*M*	*SD*	Median	Min	Max
ENL	82	150.9	7.1	150.0	137.2	165.0
PRINC	119	149.5	8.4	149.0	135.0	166.0
CBSKT	119	154.3	10.4	153.0	133.0	180.2
BRYDL	119	152.7	5.7	152.0	140.2	166.2
SLEWW	119	152.0	5.0	152.8	141.0	163.0
SECRY	119	152.3	4.9	153.0	136.0	163.0
CHRCL	119	152.6	5.2	154.0	129.0	164.0
RW17R	119	150.6	4.5	151.0	121.0	159.0

The differences between ETAs at the runway when the lead aircraft crosses each waypoint and the subsequent time interval when the spacing aircraft crosses that waypoint vary only a few seconds from the value desired at the runway. With the exception of CBSKT, the standard deviations of those parameters generally decrease as the aircraft approach the airport. The larger values at CBSKT are the result of ATC interventions in path or speeds that were scripted events to occur between the TOD (a few miles before PRINC) and CBSKT. Note that if the one questionable set of data discussed previously is removed, the standard deviations for RW17R would be significantly reduced.

3) Crossing Conformance: A key aspect to the acceptability of FDMS operations is the predictability of the aircraft's behavior, particularly for the air traffic controller. To measure this performance, the actual crossing altitudes and speeds at the constrained waypoints were compared to the published constraints. There were only a few cases where an aircraft was below the constraint altitude, and in those cases, it was by less than 200 ft. However, the spacing tool was designed to command speeds within 10% (truncated to 10 kt increments) of the published speed profile. In the majority of cases, the aircraft crossed the constrained points within this 10% boundary. There were a minority of cases, 11%, where speeds were outside the 10% boundary. The majority of these latter cases occurred at CBSKT (slowing from 310 kt to 240 kt) and SLEWW (slowing from 220 kt 180 kt). When the pilots were slow to react to the change, especially at SLEWW where a concurrent configuration change was required, the aircraft would cross the waypoint faster than desired.

4) Comparative Fuel Use: One of the main goals of a CDA is to reduce fuel use by eliminating the low altitude, level flight segments and allowing the engine to be at or near idle power for much of the descent. The benefit of airborne spacing is to maintain throughput where a pure CDA would decrease the throughput. Determining the preferred balance between these two competing goals, low fuel use and high throughput, is beyond the scope of this paper. However, fuel usage and flight time data are key to determining that balance.

As previously described, the pilot procedures when flying with and without airborne spacing are different. The first aircraft in every scenario employed VNAV PATH as its vertical navigation (VNAV) mode, using pitch to maintain the altitude profile and thrust to maintain speed. To implement the speed changes during FDMS operations, the pilot enters the ASTAR commanded speed into the MCP speed window. Speed intervention using the MCP changes the vertical guidance mode to VNAV SPEED with speed controlled by pitch and thrust set to HOLD. In this situation, the pilot must manually adjust the throttles to maintain the vertical path. Independent of the use of the FDMS procedure, these different VNAV modes alone can cause differences in fuel usage and flight time.

To measure VNAV PATH, VNAV SPEED, and FDMS effects, fast-time simulations were conducted. This fast-time evaluation showed that with respect to fuel usage, while there was a difference between VNAV PATH and spacing, it was actually an artifact of using VNAV SPEED, i.e., there was no significant difference between VNAV SPEED and spacing. The comparison in flight time showed a statistically significant difference between VNAV PATH / SPEED and spacing. However, the operational difference in this latter comparison may not be significant in that it was only 1.1% greater. One possible cause for this flight time difference is that the spacing tool was assuming forecast winds that were higher than the actual winds, which would result in a greater planned time on final approach.

IV. Conclusions

The results of numerous fast-time studies conducted on the FDMS procedures and associated ASTAR algorithm have shown the potential viability of this concept. However, several major questions still needed to be addressed regarding operational usability and acceptability by the flight crew, especially in situations involving off-nominal events. This evaluation verified that, from a pilot perspective, it is reasonable and beneficial to combine airborne spacing with CDAs. Workload ratings verify that the spacing tool was easy to use, added relatively little additional workload, and integrated well into the normal operations. There were some issues noted regarding the overall completeness of the FDMS procedures, especially those relating to the resumption of FDMS operations following an off-nominal event. Performance data show that the aircraft were able to fly CDA descents and still precisely manage their inter-arrival spacing, even when off-nominal events and forecast wind errors are introduced into the operation. FDMS presents a practical operational environment with respect to meeting speed and altitude crossing restrictions, maintaining predictable speeds and aircraft-to-aircraft spacing, and providing precision spacing at the runway threshold; all while adding relatively negligible increases to fuel usage and flight time compared to a sterile, single-aircraft CDA operation.

The results of this piloted FDMS evaluation show that airborne spacing may provide a viable solution for conducting CDA procedures for reducing air and noise pollution of aircraft operations while maintaining aircraft separation standards and without adversely affecting arrival capacity.

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