AIRBORNE PRECISION SPACING IN MERGING TERMINAL ARRIVAL ROUTES: A FAST-TIME SIMULATION STUDY

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Abstract

Researchers at NASA Langley Research Center are investigating airborne technologies and procedures to increase runway capacity by precisely spacing landing aircraft at the runway threshold. Under the concept, referred to as Airborne Precision Spacing (APS), flight crews are cleared by Air Traffic Control to follow speed cues from onboard automation to achieve precision spacing (time- or distance-based) at the threshold, relative to a designated lead aircraft. Prototypes of the onboard automation were previously used to demonstrate precision spacing operations in aircraft flying in-trail to the runway, both in simulation and in flight-test. Following those successes, the research focus has shifted to investigating the feasibility of airborne precision spacing operations across multiple arrival routes to a common runway. The prototype onboard automation has been modified to enable the new procedures, referred to as Airborne Merging and Spacing for Terminal Arrivals (AMSTAR).

As part of the testing of the new tool and operational procedures, AMSTAR operations under a range of operational conditions were studied in fast-time simulations. This study investigated AMSTAR performance in long arrival sequences composed of diverse aircraft types ranging from light jets to heavy transports. Three arrival routes with two merge points were modeled, and two different merge frequencies were evaluated. Results of the study indicate that inter-arrival spacing was achieved to well within 10 seconds even with a diverse fleet of aircraft types having dissimilar final approach speeds and unequal spacing assignments. If the entire fleet was composed of a single aircraft type, spacing was achieved to within 5 seconds of the assigned value. The number of additional speed changes required to achieve precision spacing were comparable across the different test conditions. Schedule deviations were stable and did not exceed 30 seconds over the entire one hundred aircraft simulated landing sequence.

Introduction

It is widely acknowledged that sustained growth of US air transportation may soon be challenged by system-wide congestion and delays [1,2]. New operational paradigms that leverage recent advances in technologies and redistribute responsibilities may be the answer to this impending capacity crunch. Over the past decade, researchers at NASA have been studying the use of shared traffic information, new technologies onboard aircraft, and commensurate redistributions of responsibilities among airspace users and service providers, to improve the safety, efficiency and capacity of the U.S. airspace system. One of the areas of research has been the use of traffic information on the flight deck to achieve precise spacing between aircraft arriving at capacity-constrained airports. Improved precision in runway threshold crossings leads to reduced arrival delays, and the benefits increase markedly with higher runway utilization [3].

NASA Langley Research Center has been developing and testing successive prototypes of the airborne automation and procedures that would enable precision spacing operations. The current stage of research addresses the feasibility of airborne precision spacing in multiple, merging arrival streams. In this paper, we discuss fast-time evaluations of the prototype toolset under a range of representative operating conditions. The paper commences with an outline of the new concept of operations for precision spacing in merging streams [4] and identifies parallel research efforts within the community. The design of the fast-time study and the simulation environment are then briefly described. Significant findings from the study are then discussed. The paper concludes with a summary of findings and recommendations for follow-on research.

Background

The new concept of airborne precision spacing operations in terminal area arrival flows has evolved from several decades of research into aircraftmanaged spacing [3, 5-9]. Early research indicated that, by precisely spacing aircraft across the runway threshold, variability in threshold crossing times could be reduced, thereby increasing runway throughput [5]. Further, even a small increase in runway throughput could lead to a significant decrease in landing delays for airports during high-demand conditions [3]. Simulator experiments at NASA established the feasibility of using traffic information displayed on the flight deck to enable airborne-managed precision spacing [7, 9] from crew workload and acceptability considerations. This phase of research also determined that time-based spacing was superior to distance-based spacing due to the successive speed reductions that are inherent in arrival flows.

Recent improvements in airborne display and computing capabilities, the emergence of Automatic Dependant Surveillance – Broadcast (ADS-B) technology for the sharing of traffic data, and the growing need for capacity-increasing concepts of operation have sparked renewed interest in airborne precision spacing operations. Starting in 1999, NASA researchers developed a preliminary concept of operations for terminal-area precision spacing operations [10]. Under this concept, the terminal-area air traffic controller delegates responsibility for achieving precision spacing at the runway threshold to the aircraft flight crew. Airborne automation assists the flight crew in achieving this task. The controller retains responsibility for separation and for issuing spacing requirements to the flight crew. The concept accommodates equipped (self-spacing) as well as unequipped (present-day IFR) aircraft within an arrival stream.

Research into this concept of operations is being conducted in three phases, commencing with in-trail precision spacing, progressing to precision spacing in merging arrival streams, and culminating with the limited use of maneuvering to ensure that aircraft can arrive properly spaced at the runway threshold. Prototypes of the onboard automation and operational procedures for the first phase of research (in-trail spacing) were developed and tested at NASA Langley Research Center in the 1999 – 2003 timeframe. A control law to provide flight crews with speed guidance when in-trail behind their lead aircraft [11] was incorporated into the toolset. The toolset and associated operational procedures were evaluated in piloted simulations [12] and in flight evaluations at Chicago O'Hare [13], successfully demonstrating the operational feasibility of achieving precise spacing between aircraft flying in-trail to a runway.

In Europe, precision spacing operations have been studied through several experiments [14, 15] that have evaluated the performance of exact and approximate time-delay algorithms in a variety of operational conditions, and studied the impact of these new procedures on flight crew and Air Traffic Control (ATC) operations. Although they employ some variations on the technical approach, both European and US research findings affirm the feasibility of the basic concept of airborne-managed precision spacing for in-trail arrival streams.

Precision Spacing In Merging Streams

Following the successful tests of the in-trail toolset, NASA researchers have focused on extending the algorithm, displays, and operational procedures to handle multiple arrival streams. The extended toolset is designed to enable flight crews to commence self-spacing operations while their lead aircraft is on a different arrival route to the runway. This extension offers the potential for two operational advantages. First, more time would be available to the flight crew for spacing operations. Second, properly executed spacing operations would simplify the role of ATC in monitoring aircraft merging onto a common approach to the runway. The extended toolset and associated operations are referred to as Airborne Merging and Spacing for Terminal Arrivals (AMSTAR), and are being evaluated at NASA simulation facilities.

Under AMSTAR operations, equipped aircraft enter the Terminal Radar Approach Control (TRACON) airspace on a standardized arrival route that contains lateral and vertical constraints as well as a reference speed profile. To assist in flow management between Center and TRACON controllers, these aircraft may have to meet a required or scheduled time of arrival (RTA/STA) at the TRACON entry meter-fix. Upon TRACON entry, the controller issues these arriving aircraft a precision spacing clearance, consisting of the callsign of the "lead aircraft" (which may be on a different arrival route) and the time-based relative spacing to be achieved at the runway threshold. The pilot enters this data into the AMSTAR avionics via the Multi-function Control Display Unit (MCDU). Using ADS-B data from the lead aircraft, AMSTAR provides the pilot with speed guidance cues, which could be implemented manually or directly through the auto-throttles. By following the AMSTAR speed guidance, the aircraft crosses the runway threshold at the assigned spacing interval relative to the lead aircraft. The AMSTAR speed guidance logic incorporates protection from violating pre-defined minimum separation requirements.

Experiment Design

In order to deliver precisely spaced aircraft to the threshold, AMSTAR operations must be robust to a variety of operational conditions, such as: winds and wind prediction errors; ADS-B range; a mixed fleet of aircraft types; variations in actual times of arrival at the TRACON boundary; and the frequency of merges within the arrival streams. A fast-time simulation study was designed to gain insight into the performance of AMSTAR under nominal variations in the above operating conditions. The operational ranges considered in the study are listed in Table 1, with the nominal conditions indicated in bold font.

Table 1: Values Of Independent Variables

Independent Variable	*Test Values*
ADS-B range	**80 NM** 20 NM
RTA error	Normal distribution, with standard deviation **5 seconds** 20 seconds
Wind prediction errors	No error Mean direction error of 5º **Mean direction error of 20º** Mean magnitude error of -10 knots Mean magnitude error of +40 knots
Aircraft types	**Diverse mix of types** Single aircraft type
Merge complexity	**1 arrival / merge** 5 arrivals / merge

The nominal truth wind-field ranged from 10 knots/155º at sea level to 40 knots/170º at 15000 feet. Each test condition was defined by maintaining nominal values for all parameters except the independent variable of interest. When evaluating the effects of wind-prediction errors, an extra truth wind-field condition was also tested, resulting in a test matrix containing 14 unique test conditions.

The airspace modeled for the study was the Dallas Fort-Worth (DFW) TRACON, a symmetric four-cornerpost airspace well suited to parametric studies of environmental and operational effects. Three standardized arrival routes were designed based on existing STARs for use in AMSTAR operations (Figure 1). All aircraft in the arrival flow were assumed to be AMSTAR-capable. RTA errors for each aircraft were randomly selected from a normal distribution, and each test condition was repeated 40 times in order to adequately sample the normal distribution[1]. Each such data collection run corresponded to a unique "scenario" in the simulation.

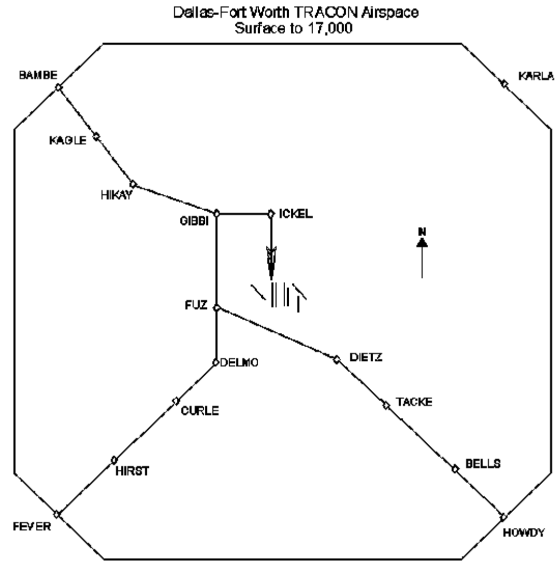

Figure 1. Experiment Airspace And Arrival Routes

Each scenario featured a sequence of one hundred aircraft entering the TRACON through the three meter-fixes, and following pre-defined arrival routes to runway 18R at DFW. The long arrival streams were modeled to detect any undesirable behaviors that could arise from the use of AMSTAR in extended operations. When a mix of aircraft types was being simulated, the spacing interval assigned to each arrival depended upon the wake-vortex category of the aircraft and that of its lead. For this study, the time-based spacing required between arrivals was calculated by converting current-day distance-based wake-vortex minima [16] into time-based minima using representative final approach speeds for each category (Table 2).

Table 2: Time-Based Aircraft Separation Minima (Seconds)

		Category of Trailing Aircraft			
		Small	***Large***	***757***	***Heavy***
Category of Leading Aircraft	*Small*	100	90	80	90
	Large	130	90	80	90
	757	170	120	100	110
	Heavy	200	150	100	110

[1] Only RTA errors were re-sampled in the repeated scenarios; aircraft type sequence and arrival route sequence were not varied.

The study was performed on simulation software called the Traffic Manager (TMX), which was developed by the National Aerospace Laboratory (NLR) of the Netherlands in cooperation with NASA. TMX [17] is a multi-aircraft desktop simulation that incorporates medium-fidelity aircraft models (based on BADA v3.6 [18]), airspace and navigation databases, the ability to model truth and predicted wind-fields, and the ability to execute, in fast-time, scripted scenarios with specific aircraft creation times and flight routes. Preparatory to this study, the TMX software was enhanced [19] to incorporate the AMSTAR algorithm, improve waypoint constraint adherence, refine aircraft models, augment the ADS-B range model, and increase the scope of data recording. A scenario generator that performed some functions of a ground-based scheduler was also custom-developed to create the large number of TMX-ready scenarios required for this study.

Discussion Of Findings

Initial analysis of the data focused primarily on the precision with which the assigned spacing was achieved at the runway threshold. Two different metrics were examined: the pair-wise spacing error (difference between actual spacing and assigned spacing), and the schedule deviation (difference between scheduled and actual threshold crossing times for each aircraft). Spacing error data collected in this fashion for different test conditions were compared to determine the impact of test conditions on AMSTAR performance. Results from this early analysis have been reported in [20, 21].

In this paper we focus on the behavior of the arrival streams in terms of three metrics – individual spacing errors, overall schedule deviation, and the number of speed changes required for precision spacing. These metrics are compared across a subset of test conditions to extract the effects of merge frequency, diverse aircraft types and categories, and lead-follower route combinations on the performance of AMSTAR in long arrival streams. To motivate the discussion, a single scenario is first examined.

Results For A Representative Scenario

As indicated earlier, each scenario involved one hundred aircraft arriving at one runway at the simulated DFW airport. The nominal test condition included randomly selected RTA errors (Figure 2) as well as an error in predicting wind direction (condition 5 in Table 1). Successive aircraft in the landing schedule entered the TRACON via different meter fixes. Therefore, every arrival encountered a single merge condition en route to the runway from the meter fix. The aircraft types in the arrival stream were randomly selected from a pre-defined list. The list contained examples of each of the four categories listed in Table 2.

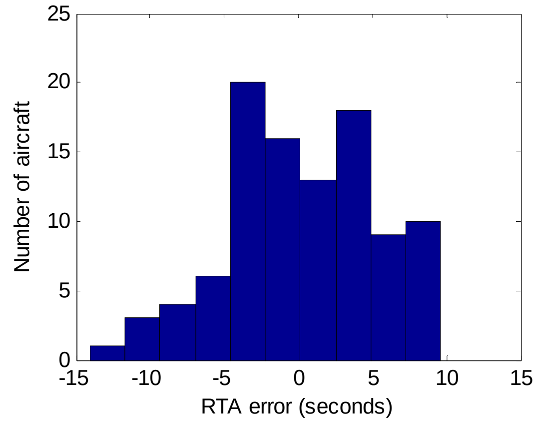

Figure 2. RTA Errors In A Nominal Scenario

The spacing errors achieved by each aircraft in the stream for a single scenario of the nominal test condition are presented in Figure 3. It can be seen that all arrivals achieved their assigned spacing within ± 5 seconds.

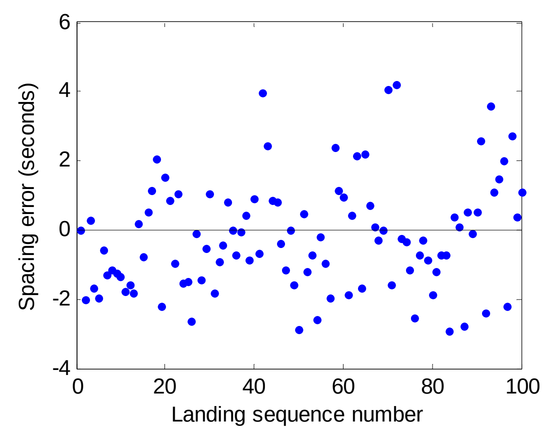

Figure 3. Spacing Errors In A Nominal Scenario

The cumulative error (schedule deviation) at each position along the stream is presented in Figure 4. The magnitude of the schedule deviation does not increase monotonically, and never exceeds 30 seconds. Considering that the time elapsed in the course of the scenario is of the order of three hours, these schedule deviation magnitudes appear insignificant.

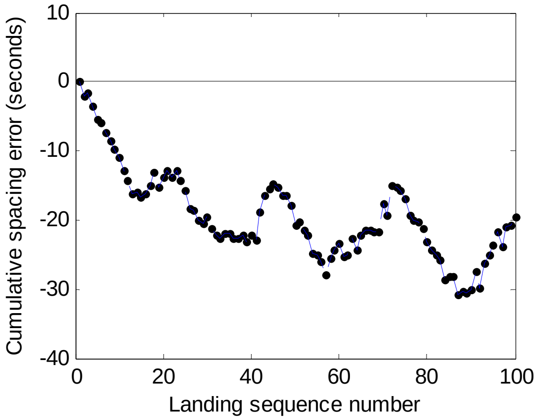

Figure 4. Schedule Deviation In A Nominal Scenario

AMSTAR achieves precision spacing using speed changes. However, frequent speed changes could give rise to ride comfort issues, and may also contribute to downstream instabilities. For these reasons, the AMSTAR system is designed to only gradually minimize the spacing error, by limiting deviations from the reference speed profile. Speed profiles commanded by AMSTAR for a few positions in the arrival stream from BAMBE are compared to the standard profile in Figure 5, demonstrating this AMSTAR design approach.

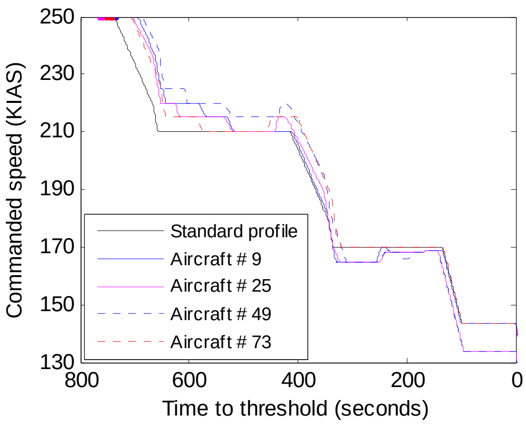

Figure 5. Speed Profiles In A Nominal Scenario

Figure 6 is a histogram of the number of speed changes of different magnitudes for aircraft #25 in the stream. The speed changes close to ±5 knots are those introduced by AMSTAR, while the other changes are intrinsic to the arrival route. Therefore, for this example, AMSTAR operations added six speed changes to the basic five of the arrival route.

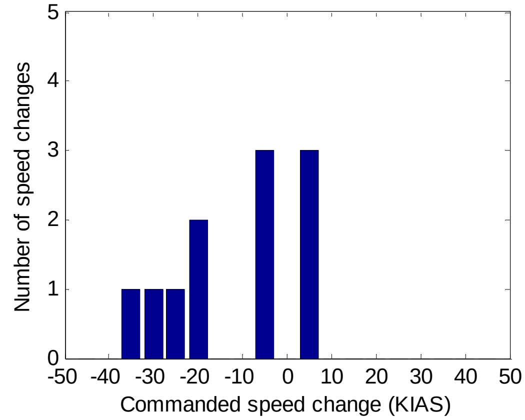

Figure 6. Sample Histogram Of Speed Change Magnitudes In A Nominal Scenario

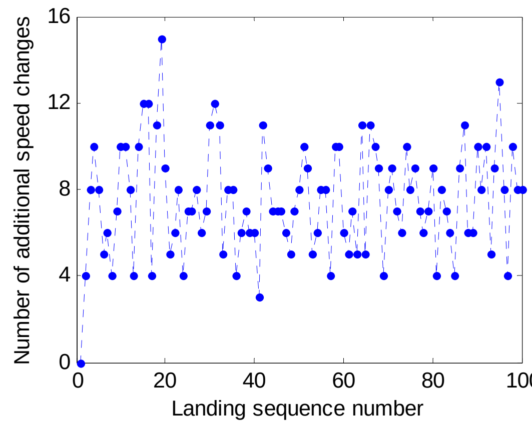

Figure 7. Additional Speed Changes In A Nominal Scenario

The number of additional speed changes experienced by all aircraft in the stream is presented in Figure 7. While there are outliers in these data, the number of speed changes required for precision spacing generally does not increase with position in the landing sequence, suggesting that the AMSTAR design approach may be achieving the goal of protecting stream stability.

Results For The Nominal Test Condition

The above discussion examined a typical scenario under nominal test conditions. We now discuss results averaged across 40 samples of the nominal test condition. Spacing errors for each position in the stream, averaged across the 40 scenarios (Figure 8), indicate that individual spacing errors remain bounded within ±10 seconds. Figure 9 presents the mean schedule deviation at each position in the stream, indicating that AMSTAR achieves a schedule deviation of no more than 30 seconds over three hours of simulated operations under nominal test conditions.

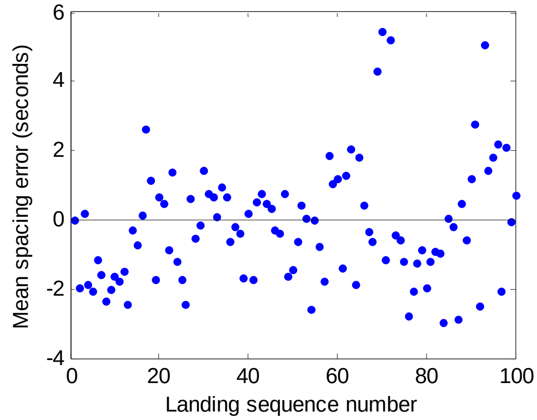

Figure 8. Mean Spacing Errors In Nominal Test Condition

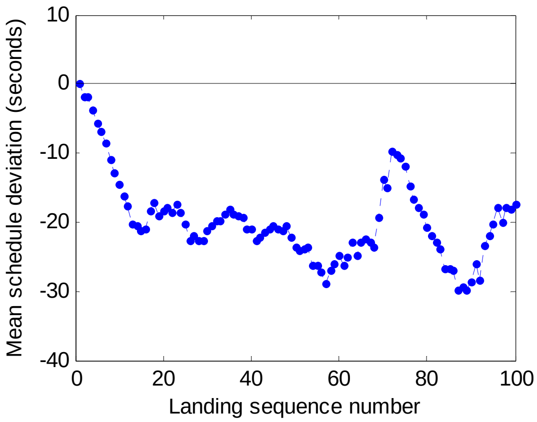

Figure 9. Mean Schedule Deviation For Nominal Test Condition

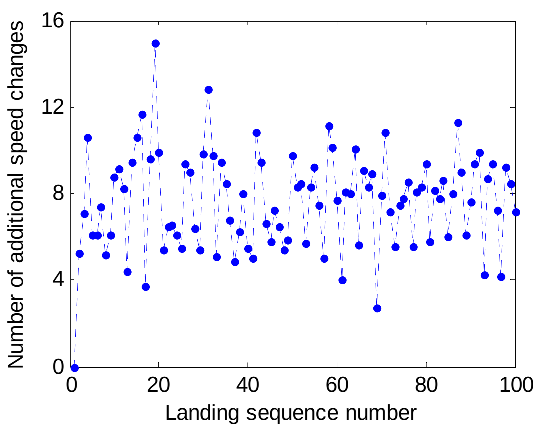

Figure 10. Mean Number Of Additional Speed Changes In Nominal Test Condition

Figure 10 presents the mean number of speed changes introduced by AMSTAR for each position in the stream, once again indicating that the number of additional speed changes generally does not increase with position in the landing sequence.

Comparing the mean spacing error data of Figure 8 with the sample scenario data of Figure 3, it is noteworthy that the same positions in the arrival stream generally performed poorly across all repeats of the test condition. To determine the causes of this behavior, the spacing error data was analyzed in terms of arrival route, aircraft weight category, and lead-follower weight category combination. Figures 11, 12 and 13 document the results of this analysis.

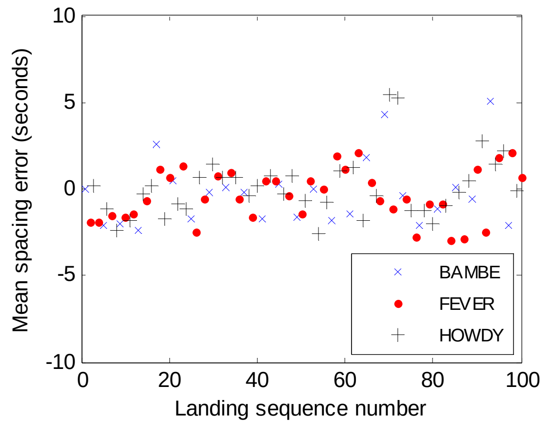

Figure 11. Mean Spacing Errors By Entry Fix Name

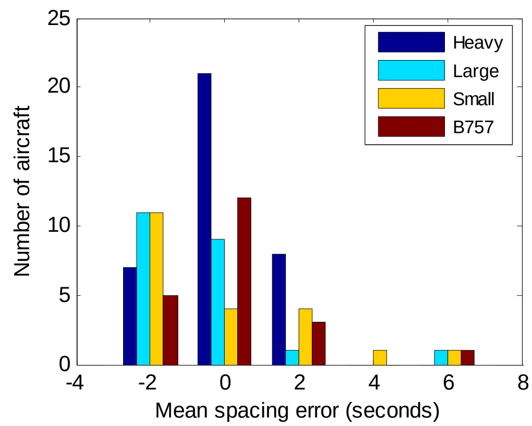

Figure 12. Histogram Of Spacing Errors In Nominal Test Condition, Averaged By Aircraft Category

The data in Figure 11 suggests that the arrival route was not the primary cause of large spacing errors. The histogram of spacing errors averaged by aircraft category (rather than position in the stream), depicted in Figure 12, suggests that ‘small’ aircraft generally experienced a larger spread in spacing errors, although the mean error is comparable to those for the other categories. On the other hand, Figure 13 suggests that aircraft following a 'small' aircraft (data labeled 'SH', 'SL', 'SS' and 'SB' in Figure 13) generally experienced higher spacing errors than aircraft with lead aircraft from the other categories.

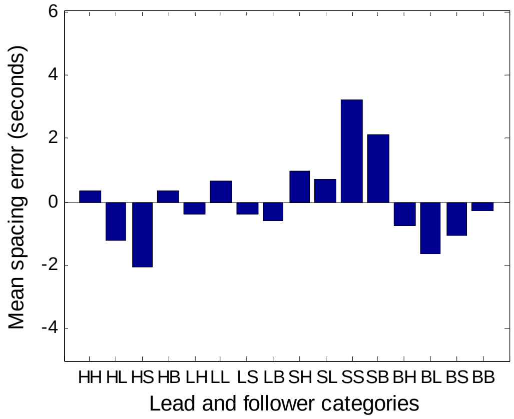

Figure 13. Spacing Errors In Nominal Test Condition, Averaged By Lead And Follower Aircraft Categories (Nomenclature: H = Heavy, L = Large, B = B757, S = Small, HL = Heavy aircraft leading a Large aircraft, etc.)

Closer examination of the landing sequence confirms that the aircraft experiencing the highest spacing errors for the nominal test condition (positions 70, 72 and 93 in the sequence) were all following 'small' aircraft. Further analysis is underway to determine the causes for this behavior.

Effects Of Homogeneity In The Arrival Stream

As indicated in Table 1, data was also collected for an arrival stream composed entirely of a single type of aircraft, with all other test variables maintained the same as the nominal test condition. Comparison of these data with those from the nominal test condition highlights the effects of aircraft type diversity on AMSTAR performance. Figures 14, 15 and 16 present, respectively, the mean spacing errors, mean schedule deviation and mean additional speed change counts for each position in a homogenous arrival stream.

The data of Figure 14 indicate that aircraft in this arrival stream experienced a much smaller range of spacing errors than in the diverse stream. These data and the schedule deviation data (Figure 15) suggest that the homogenous stream stabilizes after about 20 arrivals, a phenomenon not observed in the diverse stream.

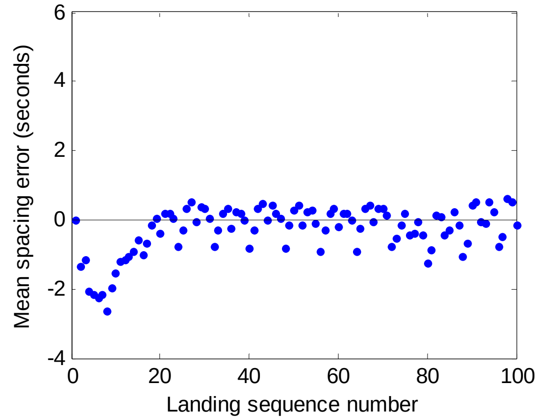

Figure 14. Mean Spacing Errors For Homogenous Arrival Stream

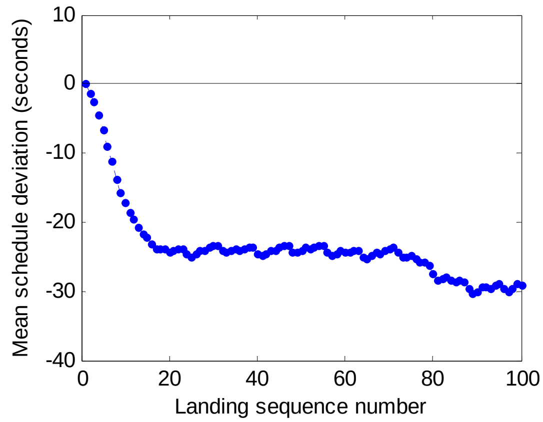

Figure 15. Mean Schedule Deviation For A Homogenous Stream

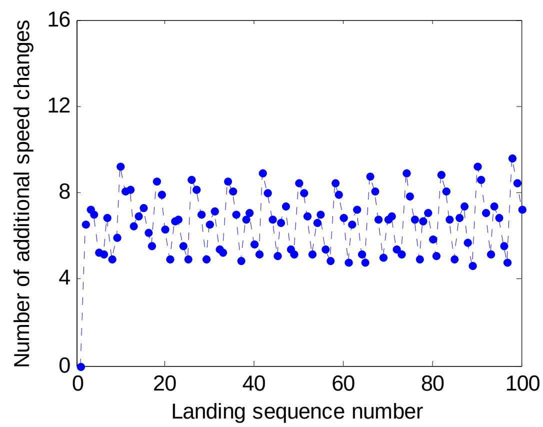

Figure 16. Mean Number Of Additional Speed Changes For A Homogenous Stream

The average number of speed changes experienced at each position in the stream (Figure 16) also indicate an initial transient, but the subsequent data clearly depict a pattern that repeats itself after every eighth arrival. This is noteworthy, since the landing sequence for the study was itself a repeated sequence of entry-fixes, with eight airplanes in each sequence. These data hence suggest that certain arrival route combinations repeatedly experienced more speed corrections.

Further analysis (Figure 17) indicates that the higher speed change counts are associated with aircraft from the southwest, landing behind aircraft from the northwest entry fix. While intriguing, this behavior is completely absent in the more realistic case of a diversified fleet of arrivals. The causes of this effect are still being investigated.

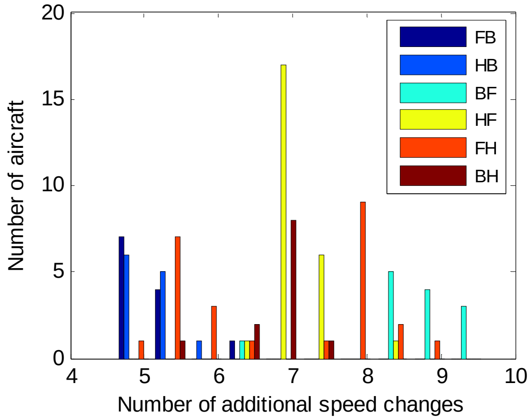

Figure 17. Histogram Of Mean Number Of Additional Speed Changes For Homogenous Stream, Grouped By Entry Fix Combination (Nomenclature: F = FEVER, B = BAMBE, H = HOWDY, FB = Aircraft from FEVER leading aircraft from BAMBE, etc.)

Effects Of Merge Complexity

In the nominal test condition, every arrival encountered a merge situation. This feature of the experiment design was intended to maximize the collection of data on precision spacing in merging arrival streams. For comparison purposes, data was also collected for a landing sequence that was composed of 'blocks' of five aircraft from each of the three TRACON entry fixes. Figures 18, 19 and 20 present the mean spacing errors, mean schedule deviation and mean speed change counts as a function of position in the landing stream for this test condition.

The mean spacing errors for each position in the stream are depicted in Figure 18, indicating that, under this test condition, the spread in spacing errors slightly exceeded that achieved with the nominal merge condition.

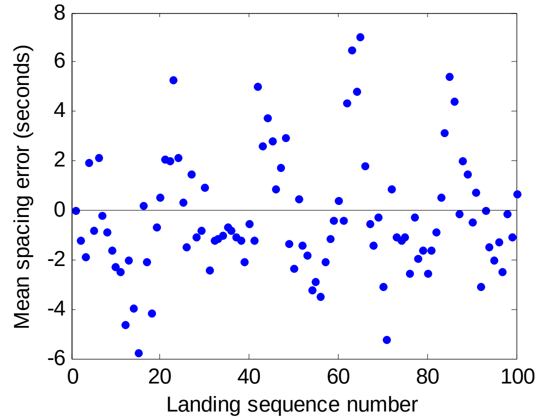

Figure 18. Mean Spacing Errors For Block-Merge Test Condition

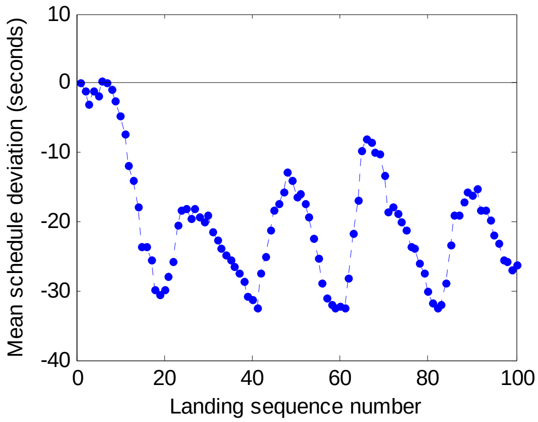

Figure 19. Mean Schedule Deviation For Block-Merge Test Condition

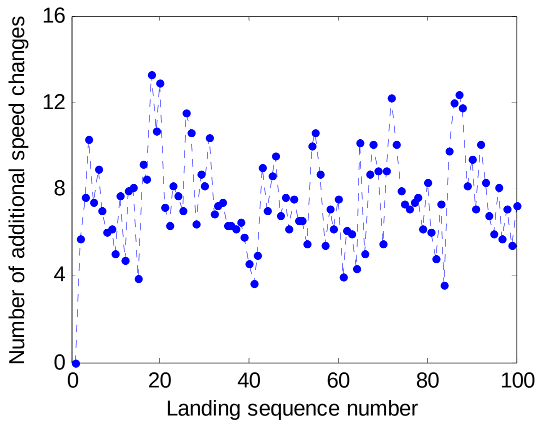

Figure 20. Mean Number Of Additional Speed Changes For Block-Merge Test Condition

The schedule deviation for this test condition (Figure 19) is similar in magnitude to the nominal test condition, but the data exhibit marked periodicity with about 20 arrivals between successive peaks or troughs. This periodicity may be the result of route-dependant spacing error behavior, or may be an artifact of a route-dependant scheduling bias. The data collected in this study were inadequate to confirm or dispel these hypotheses.

The average number of speed changes experienced for each position along the stream is depicted in Figure 20. As with the nominal test condition, there is no evidence of an increase in the number of speed changes as position in the stream is increased. However, these data also suggest some periodicity, while the magnitudes are generally similar to those experienced under the nominal test condition. Further data collection and analysis are required to fully understand these behaviors.

Summary and Conclusions

A series of fast-time simulations of a new concept of operations for terminal arrivals was conducted. Under the new concept, referred to as Airborne Merging and Spacing for Terminal Arrivals, or AMSTAR, suitably trained flight crews are cleared by ATC to achieve precision spacing relative to a designated lead aircraft at the runway threshold, using new onboard automation for speed guidance. The fast-time evaluations used a medium-fidelity implementation of the new toolset, and were performed using desktop simulation software that modeled several aircraft types.

The results of the study indicate that the AMSTAR concept and prototype onboard systems performed satisfactorily under the nominal test condition, which included errors averaging up to 20 degrees in predicted wind direction, as well as bounded-random errors in the time when aircraft entered the TRACON. Diversity of aircraft types in the arrival stream increased spacing errors relative to a homogenous arrival stream, and initial analysis suggests that the presence of light jets in the stream may have contributed to this effect. Reducing the merge frequency appears to slightly increase the range of spacing errors and the magnitudes of schedule deviation.

Further evaluations of AMSTAR operations are required to fully understand the interdependence of aircraft type diversity and spacing error behavior, and the effects of merge frequency on AMSTAR performance. A new series of fast-time studies are currently being planned at NASA Langley to pursue these research objectives.

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