An Exploratory Study of Runway Arrival Procedures:

Time-Based Arrival and Self-Spacing

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The ability of a flight crew to deliver their aircraft to its arrival runway on time is important to the overall efficiency of the National Airspace System (NAS). Over the past several years, the NAS has been stressed almost to its limits resulting in problems such as airport congestion, flight delay, and flight cancellation to reach levels that have never been seen before in the NAS. It is predicted that this situation will worsen by the year 2025, due to an anticipated increase in air traffic operations to one-and-a-half to three times its current level. Improved arrival efficiency, in terms of both capacity and environmental impact, is an important part of improving NAS operations. One way to improve the arrival performance of an aircraft is to enable the flight crew to precisely deliver their aircraft to a specified point at either a specified time or specified interval relative to another aircraft. This gives the flight crew more control to make the necessary adjustments to their aircraft's performance with less tactical control from the controller; it may also decrease the controller's workload. Two approaches to precise time navigation have been proposed: Time-Based Arrivals (e.g., required times of arrival) and Self-Spacing. Time-Based Arrivals make use of an aircraft's Flight Management System (FMS) to deliver the aircraft to the runway threshold at a given time. Self-Spacing enables the flight crew to achieve an ATC assigned spacing goals at the runway threshold relative to another aircraft. The Joint Planning and Development Office (JPDO), a multi-agency initiative established to plan and coordinate the development of the Next Generation Air Transportation System (NextGen), has asked for data for both of these concepts to facilitate future research and development. This paper provides a first look at the delivery performance of these two concepts under various initial and environmental conditions in an air traffic simulation environment.

Introduction

The Federal Aviation Administration (FAA) and industry forecast that air traffic operations are expected to increase 150% to 300% over the next two decades. These increases in operations are expected to stress the National Airspace System (NAS), which is functioning near full capacity, to unmanageable levels. When this is coupled with the fact that there is a proportional economic relationship between the gross domestic product (GDP) of the United States (U.S.) and air travel, investing in the revitalization of this vital infrastructure is critical if the U.S. intends to remain a major world economy. Analysis of even conservative growth estimates shows a significant lack of existing and planned capacity.

The U.S. response to this looming crisis was the formation of the Joint Planning and Development Office (JPDO) which would facilitate the Next Generation Air Transportation System (NextGen) activities. The JPDO's objectives are to develop the vision for NextGen, to spearhead planning, and to coordinate research, demonstrations and development required to achieve this vision. The goal of NextGen is to complete a system-wide and transformation of the NAS that leads to a new set of capabilities that will allow the system to respond to future needs of the U.S. transportation system, thus transforming the NAS from a ground-based system of air traffic control (ATC) to a aircraft-based system of air traffic management. [1]

To focus the research community and progress towards implementable systems, the JPDO has identified a series of operational improvements and their supporting research and development needs. Many of these needs are research to help select between possible alternate solutions to the same problem. One such area is the move towards time-management of arrivals at busy airports. In particular, should the arriving traffic be controlled to an inter-aircraft interval, self-spacing, or to a fixed schedule, such as a required time of arrival. The paper presents a first step towards answering some of those questions.

NASA has been developing and testing concepts and technology to support self-spacing operations for airport arrivals.[3-11] The current concept allows the controller to assign a reference aircraft and a time interval relative to the reference aircraft to achieve by the runway threshold. Following aircraft then use Automatic Dependent Surveillance-Broadcast (ADS-B) data from the reference aircraft and the expected routing of both aircraft to provide speed guidance to achieve the assigned spacing. To support this study, the on-board automation prototype has been extended to achieve a required time of arrival.

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I. Experiment Design

A. Arrival Spacing Concepts

Well designed concepts of operation were needed to ensure an accurate assessment of the different control paradigms, namely relative spacing or fixed time.

The concept used for the fixed schedule concept, hereafter called Time-Based Arrivals or TBA, allows each arriving aircraft to be assigned a required time of arrival (RTA) at the runway threshold and to adjust their speed to achieve that time. Implementation of TBA requires that a ground-based scheduler calculate an RTA for the aircraft at the runway. The RTA must be consistent with the controller's need to maintain a safe and efficient flow. Once calculated, the aircraft's onboard automation is used to manage its speed to meet the RTA. Any aircraft requiring it can receive a new RTA that allows it to meet its objective time at the runway threshold.[12-14] In real-world operations the onboard automation would likely be resident in the Flight Management System (FMS). However, for this study, the same speed guidance system that supports the self-spacing (SS) operations was used to meet the RTA. One advantage of using the same speed guidance system for both concepts is that the details of the control law are no longer a confounding variable. The spacing tool, called ASTAR, is also able to use sensed winds from the ownship as well as other traffic to update the internal wind model making the trajectory prediction more accurate. See section II.F for more details on how ASTAR works.

The SS concept is based on NASA's Airborne Precision Spacing research of the last several years.[10] In this concept, an aircraft is assigned a reference aircraft and a time interval to land following that reference aircraft. The spacing aircraft then uses ADS-B data from the reference aircraft and ASTAR provides speeds in order to precisely achieve the assigned interval at the runway threshold. The interval is assigned by the controller to meet their separation and flow requirements. Pairs of spacing aircraft can be linked together to form a chain of aircraft, each spacing relative to the one in front of it.

B. Study Objectives and Test Variables

A complete comparison of these two concepts to manage arrival flows is a multi-step process. This study was designed to be a first-look at some of the system-wide metrics to guide further study. It does not address questions such as the cost of such systems; the user's derived benefits of equipping for these operations, the human workload issues or requirements of the scheduling tool.

Four questions were identified that could be answered within the scope of this study:

1. What is the performance impact when speed control responsibility is transferred from ATC to the aircraft?
2. Is it operationally feasible to mix both Time-Based Arrival and Self-Spacing operations within the same arrival stream?
3. How do Time-Based Arrival, Self-Spacing and mixed operation procedures perform with a forecast wind error?

4. What is the impact of adding a gap in the arrival stream after the aircraft have started their Time-based Arrival or Self-Spacing operation?

Deciding the proper time to transfer the spacing task to the aircraft could be a trade-off. Transferring early allows the aircraft to overcome greater errors and to do so with smaller changes but could allow the build-up of instabilities (e.g., over control of speed). A late transfer would minimize the chances of instabilities or disturbances having a negative effect but would allow very little time to make any timing corrections that are needed. Transfer points of 30 NM flight distance from the runway threshold, the entry into the Terminal Radar Control (TRACON) facility, approximately 40-75 NM, and just prior to top-of-descent, around 134 NM from the runway, were each examined.

Since both TBA and SS operations will likely require new equipment and that equipment could be used for other operations, it is not assumed that all arriving traffic will be equipped to perform the same operations. Therefore, in addition to the two cases where the entire arrival stream is uniformly equipped, one for TBA, one for SS, a mixed procedure case was considered. In this condition each aircraft was randomly assigned to be equipped with either TBA or SS capabilities. The scheduling tool was aware of the aircraft's capability and assigned an appropriate timing goal, such that one aircraft was assigned an RTA while the trailing aircraft was assigned a relative interval behind the first. All aircraft were ADS-B out equipped and thus could be a reference aircraft for a self-spacing aircraft.

Previous research[18] has shown that the accuracy of the wind forecast used to create the arrival schedule and used by ASTAR for trajectory prediction is critical to the success of self-spacing operations. The difference between the along-track component of the truth and forecasted winds represents a speed error that must be overcome. It is expected that a similar effect would occur for the TBA operations. However, in SS operations the whole stream of aircraft will react in concert to the forecast errors while for TBA operations, each aircraft reacts independently. If, in SS operations, the forecast error causes an aircraft to arrive later than scheduled, the trailing aircraft has been correcting for that since they started the operation and will attempt to maintain the required following time. In TBA operations, the trailing aircraft "knows" nothing of what the leading aircraft is doing and this may result in inadequate spacing along the arrival.

If the spacing between two aircraft in the arrival is increased, (e.g., to insert a new aircraft or allow a change in the runway use plan) after the schedule is frozen, all subsequent aircraft will need to delay by that amount. The manner in which the delay is communicated differs between the two operations. In TBA, each affected aircraft will be given a new RTA and will begin meeting that time. This would require communications with every aircraft but each will immediately start implementing the delay. In SS operations, only the aircraft immediately following the change is notified and will start to slow to achieve the new interval. The trailing aircraft will detect the slower speed and will have to adjust accordingly to meet its spacing interval, which is unchanged. The delay will propagate back through the stream in this manner. Performance differences between these two approaches were investigated.

A full factorial design was used for the first three questions resulting in a 3x2x3 matrix (18 test conditions). To address the fourth question, gap creation, two additional conditions were added: TBA and SS with no wind forecast error and starting at the top of descent. The full list of independent variables is shown in Table 1.

Table 1: List of independent variables and their conditions for this study.

Procedure	*Wind Forecast*	*Freeze Horizon*
Time-Based Arrivals	No Forecast Error	30 NM Arrival Fix
Self-Spacing	50% Forecast Error	TRACON Entry
Mixed (50% TBA, 50% SS)		Top-Of-Descent

C. Scenario Design

The baseline scenario was selected to match previous NASA research studies.[8, 11, 18] Four arrival routes, starting in en route airspace, leading to a single runway were used (see figure 1). Each traffic scenario consisted of an ordered list of 50 aircraft, the landing sequence, with each randomly assigned an arrival route, aircraft type and appropriate weight. An assigned spacing interval was determined for each pair based on the aircraft type of each which accounted for the required wake separation distance, the range of final approach speeds and an additional 10 seconds. All 50 aircraft would experience the same wind field which consisted of a truth wind and a forecasted wind. Figure 2 depicts the effective wind field that the aircraft flew through. The truth winds are what the aircraft actually flies through and is used for the calculation of movement. The forecast winds are used by the aircraft and scheduling tool for trajectory calculations. The difference between these winds produced a wind forecast error of fifty percent. The wind strength is given by $V(h) = V_{30} \left(\frac{h}{30}\right)^{1/7}$V = V_30 (h/30)^1/7 where V_{30} is the wind strength at 30 feet above ground level and *h* is the altitude above ground level. The forecasted winds were then used to determine the optimal starting time at the appropriate starting point based on the assigned route and freeze horizon. An additional delivery uncertainty was added by randomly adjusting the start time to model delivery imprecision to that point. The uncertainty was a normal distribution with a standard deviation of 20 s (30 nm freeze horizon), 30 s (TRACON) or 40 s (top-of-descent).

Based on previous research, it was expected that seven repetitions of this scenario for each test condition would provide sufficient data for statistical analyses. The repetitions differed by changing each of the randomly selected quantities, such that each had a different landing sequence, aircraft types and delivery uncertainty but the same winds and spacing intervals per pair.

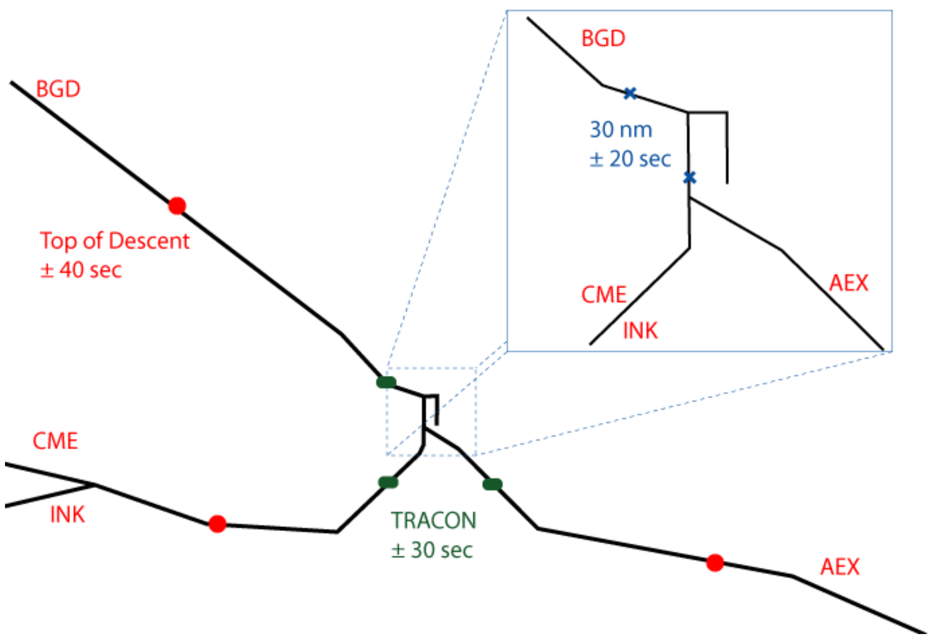

Figure 1: Schematic of the four arrival routes used in the simulation with starting points and initial uncertainties marked.

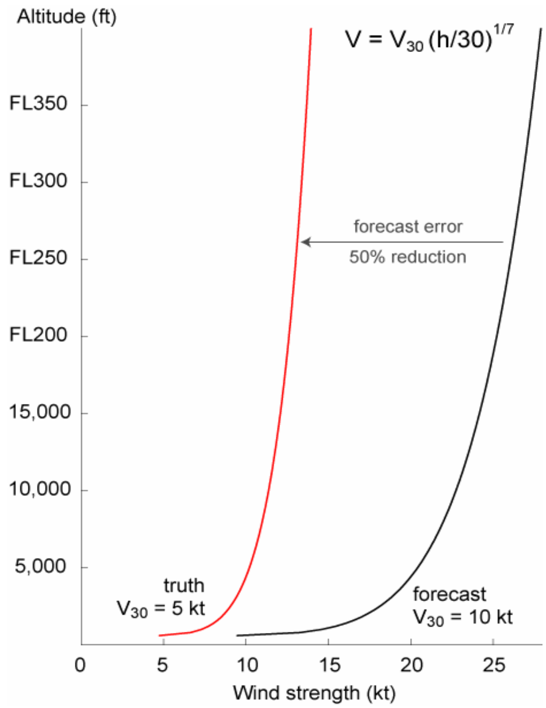

Figure 2: Plot of Truth and Forecast Winds and Wind Forecast Field

D. Metrics

The two main metrics studied were the inter-arrival spacing and schedule deviations. The inter-arrival spacing deviation is the difference between the scheduled spacing between consecutive aircraft and the achieved spacing. Of course, the SS aircraft are controlling to this interval and are therefore expected to perform better than the TBA aircraft. The schedule deviation is the difference between the schedule arrival time and the actual arrival time. The TBA aircraft are controlling to the schedule and are thus expected to perform better. If this is borne out, it would then be an operational decision whether arrivals are preferred with precise spacing with some schedule uncertainty or precise scheduling with uncertain spacing.

The number of speed changes required by ASTAR to achieve the timing goal is indicative of how hard it was to achieve the goal and the overall stability. For this study ASTAR was set to achieve maximum precision which results in speed changes of 1 kt or 0.01 Mach. While this might be acceptable for a system where the speed commands are integrated with an auto-throttle system, such frequent, small changes would likely overload a flight crew responsible for manually implementing the changes. ASTAR has additional parameter sets which produces, fewer, but larger, speed changes with the effect of reduced precision in the final goal. The balance between precision and possible crew workload, or other effects such as passenger comfort or engine wear, is left for future studies.

E. Simulation Environment

This study used the Traffic Manager (TMX) simulation platform.[15, 16] TMX is a low- to medium-fidelity, traffic simulator that can be used in either a standalone mode for real-time or fast-time simulations or networked with one or more flight simulators to provide a realistic traffic environment for these simulators. TMX can represent over 80 different aircraft types using a 6 degree of freedom model. The performance data for the TMX aircraft come from the Eurocontrol Database of Aircraft Data[17] with enhancements derived at NASA Langley Research Center. Each aircraft has representative auto-flight and auto-throttle models that include basic altitude, heading and speed modes plus lateral and vertical navigation modes. The ASTAR speed guidance has been incorporated into TMX [16] and can be used directly by the auto throttles or via a pilot model following commanded speeds. TMX also includes both truth and forecast wind fields that can vary in both horizontal and vertical position; an ADS-B model that includes realistic report content and a configurable distance-based reception probability; and airspace infrastructure such as navigation aids. TMX was developed by the National Aerospace Laboratory of the Netherlands and enhanced by the National Institute of Aerospace and NASA Langley Research Center.

F. Airborne Spacing for Terminal Arrival Routes (ASTAR)

The Airborne Spacing for Terminal Arrival Routes (ASTAR) algorithm created at NASA Langley is capable of spacing aircraft based on an absolute schedule or on a relative interval behind the preceding aircraft. It is assumed that the aircraft are following published arrivals such as a Standard Terminal Arrival Route (STAR) with altitude and speed constraints. ASTAR builds a four-dimensional trajectory based on the STAR with constraints and controls the Estimated Time of Arrival (ETA) at the runway threshold to meet the assigned timing goal. For self-spacing operations, it repeats the same calculation for the reference aircraft and controls to the difference between the ETAs.

To maintain a predictable and stable arrival flow and minimize workload increases for the flight crew, the onboard spacing software is limited to making small speed corrections around a nominal speed profile. The nominal speed profile is the speed schedule for that segment of the flight. Filtering and gain scheduling techniques are also used to reduce or inhibit speed corrections based on the distance the aircraft is from the runway. This avoids over-reacting to small deviations while countering large deviations and adds to the overall stability of a stream of spacing aircraft.

ASTAR also includes the planned final approach speed in the ETA calculation thereby compensating for one of the greatest influences invariance from desired arrival time, the different final approach speeds flown by various types of aircraft at differing weights during the final portion (typically the last 5 miles) of the instrument procedure.

G. Study Limitations

Since this was a first-look study several simplifying assumptions were made. First, the arrival sequence and schedule were set all at once and fixed prior to the scenario beginning. This meant that as disturbances arose the schedule could not be adjusted to account for them. In a normal operational environment, if the first several aircraft being scheduled encountered an unexpected headwind, the later aircraft would be scheduled slightly later to account for the slower speeds. This did not happen in this simulation.

Past studies[18] suggest that a combination of the BADA models and the flaps and spoiler model within TMX allows the aircraft to decelerate more rapidly than was observed in higher fidelity simulators. This would allow for tighter speed control, and better performance, in this simulation than in actual operations.

II. Results and Discussion

A detailed analysis was conducted in order to determine how each of the arrival procedures performed under the test conditions of this study. . It was hoped that the metrics of interest, spacing, scheduling, speed changes, and aircraft throughput per hour would reveal a measurable difference in the performance of the arrival procedures TBA and SS. Indeed, there are metrics of interest that show bias toward one arrival procedure over another. For instance, TBA's concept of operation to control an aircraft to a schedule at the runway threshold implies that its scheduling performance would be superior to that of SS or Mixed. However, it was important to observe both the biased as well-as the equitable metrics of interest in order to assess the overall performance of each arrival procedure. Results of this study are presented separately for the no wind forecast error and wind forecast error conditions.

A. Inter-arrival Spacing

The assigned spacing intervals for this study, which are the same for both arrival procedures, are times based on required wake vortex separation distances. The conversion was based on the slowest expected speed for each wake category plus ten seconds to ensure the normal variability would not violate the required separation distance. The spacing error is then difference between the assigned value and the observed value. A negative spacing error indicates that a trailing aircraft is closer to the leading aircraft then the assigned interval. Figures 3 and 4 shows the spacing error statistics for the no wind forecast error and wind forecast error conditions, respectively. The key result is that under all conditions, the operating procedures and freeze horizon, the means were near zero seconds and the standard deviations were never larger than ten seconds. Of particular note is that the performance of mixed operations was not significantly different than either a fully SS flow or a fully TBA flow. A three-way ANOVA test does not show any statistically significant differences in the means at the 95% confidence level ($p > 0.36$ for all three independent variables). The maximum standard deviation, which is the largest standard deviation observed for each arrival procedure while operating under each wind condition, provides an indication of how much of an effect the forecast error had on the performance of the arrival procedures; see Table 2. The largest effect was on the SS operations although it becomes no worse than the TBA operations. Further investigation will be required to understand why TBA seems insensitive to the wind forecast errors. Operationally, these standard deviations would have similar impacts. During transition arrival, the effect of the freeze horizons on the spacing performance is small and considered operationally insignificant.

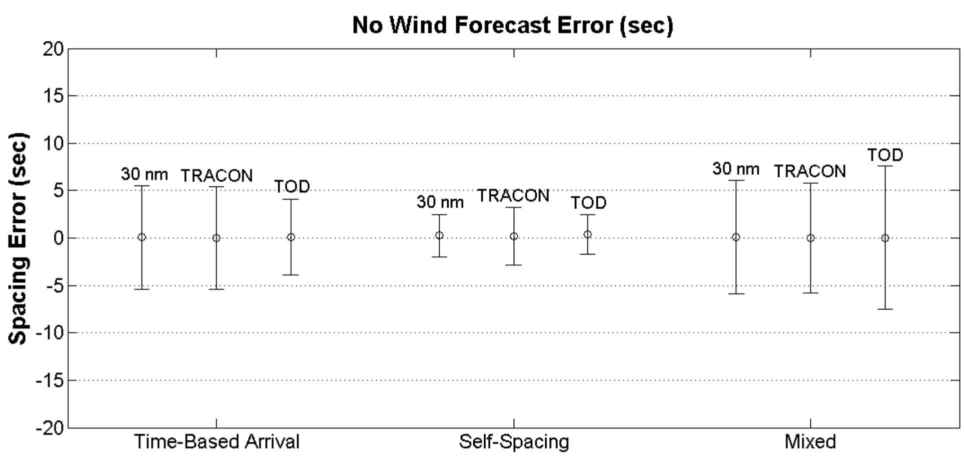

Figure 3: Arrival procedures spacing error performance with no wind forecast error.

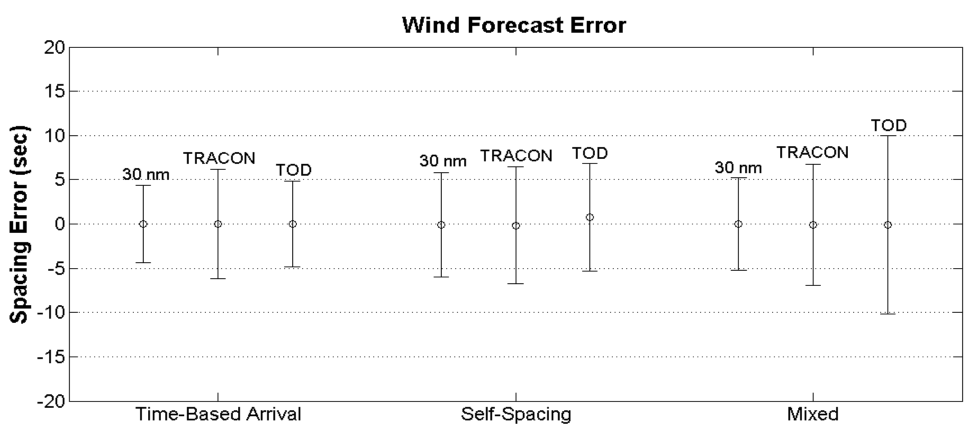

Figure 4: Arrival procedures spacing error performance with wind forecast error.

Table 2: Arrival procedures' difference between maximum standard deviation spacing error with and without wind forecast error.

Procedures	*Maximum Standard Deviations with no Wind Forecast Error*	*Maximum Standard Deviations with 50% Forecast Error*	*Percent Differences*	*Absolute Differences*
TBA	5.50 sec	6.20 sec	12.7%	0.70 sec
SS	3.10 sec	6.60 sec	113%	3.50 sec
Mixed	7.50 sec	10.1 sec	34.7%	2.60 sec

B. Scheduling Deviation

The scheduling deviation metric shows how well each of the arrival procedures performed at achieving their scheduling goal at the runway. Figure 5 shows that aircraft performing TBA, SS, or mixed arrival procedures were, by and large, arriving late to schedule while under no wind forecast error by as much as eighteen seconds, in the case of SS. TBA's conceptual design is to control the aircraft to a schedule at the runway and at this metric its performance was superior to those of SS and Mixed. Comparably, SS had noticeably larger means and standard deviations than both TBA and Mixed. This is attributed to the fact that SS does not control to a schedule. If the first aircraft was early or late relative to its scheduled time then this scheduling error would be passed on to the second aircraft in the arrival stream which is spacing relative to their lead and not trying to follow the schedule. Therefore, this initial error would propagate back through the arrival stream. To partially mitigate this effect, the first aircraft in the SS streams were assigned an RTA. This accounts for the larger differences in standard deviations and mean scheduling errors for SS that are seen in figures 5 and 6.

The arrival procedures' scheduling deviation performance with wind forecast error is depicted in Figure 6. Comparing the mean scheduling error of figure 6 to that of figure 5 makes it is evident that the wind forecast error created an effective tail wind, which resulted in all procedures delivering their aircraft earlier than scheduled. Observing the differences in the standard deviations shown in figures 5 and 6 reveals that there is less than a fifty percent change in value overall (see Table 2).

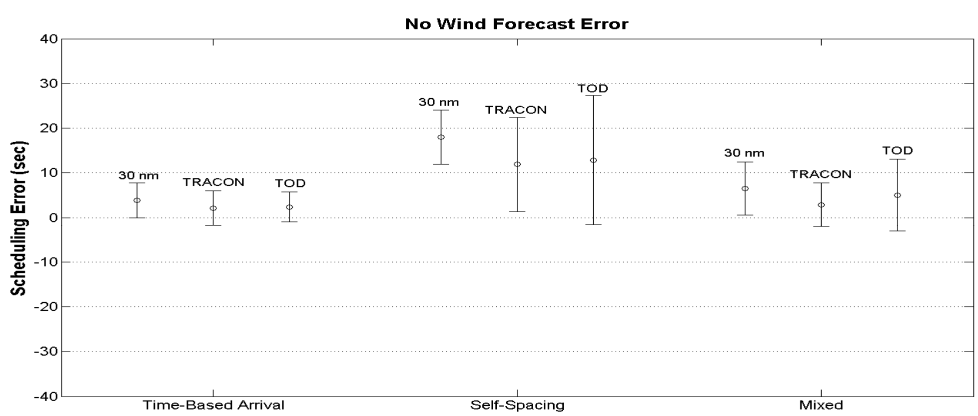

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Figure 5: Arrival procedures scheduling deviation performance with no wind forecast error.

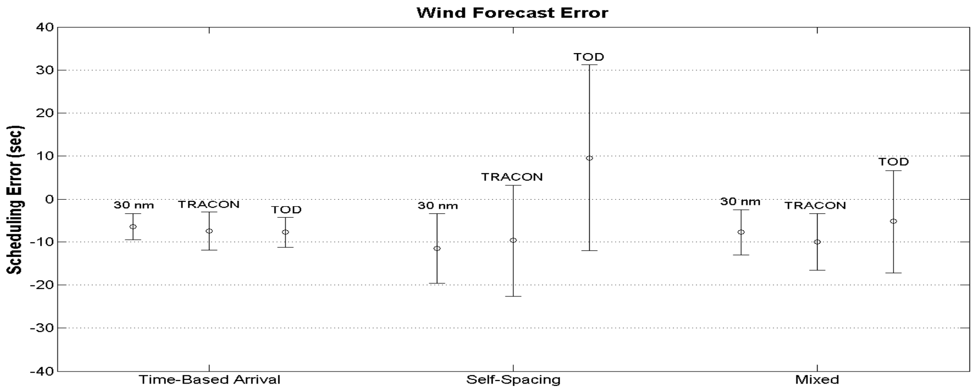

Figure 6: Arrival procedures scheduling deviation performance with wind forecast error.

Table 3: Arrival procedures' difference between maximum standard deviation scheduling error with and without wind forecast error.

Procedures	*Maximum Standard Deviations with no Wind Forecast Error*	*Maximum Standard Deviations with 50% Forecast Error*	*Percent Differences*	*Absolute Differences*
TBA	3.93 sec	3.02 sec	-23.2 %	0.91 sec
SS	14.5 sec	21.7 sec	49.6%	7.20 sec
Mixed	8.11 sec	12.0 sec	48.0%	3.89 sec

C. Speed Change Analysis

The speed change metric is considered an equitable metric. Meaning, the performance of the arrival procedures at this metric is not biased toward the concept of operation of the procedure being observed. The Speed Change metric is analyzed, in lieu of pilot data, to determine how many control commands automation tools issued so that an aircraft performing an arrival procedure could achieve its goal of either spacing or meeting an RTA while operating under no wind forecast error or wind forecast error. The speed changes are at 1kt intervals and it is anticipated that there will be an increase in speed changes for all procedures when wind forecast error is introduced. The number of speed changes for TBA at the freeze horizons under no wind forecast error had an average no greater than twenty-three, for SS it was thirty-five, and twenty-seven for Mixed. Comparing the average speed changes of figure 7 and figure 8 reveals a larger speed change increase for automation tools used in performing TBA at all freeze horizons than for the two other procedures. Observing the percent difference of the mean number of speed changes, see Table 4, offers greater insight into tool performance. TBA showed an 80.2% increase in speed changes compared to a 9.10% and 34.7% increase for SS and Mixed respectively. This indicates that the aircraft automation tools used to conduct TBA procedures issued more commands to achieve spacing and scheduling goals than that of SS and Mixed. From this comparison it was determined that there were some operational difficulties in achieving spacing or scheduling goals for TBA and Mixed when operating with wind forecast error.

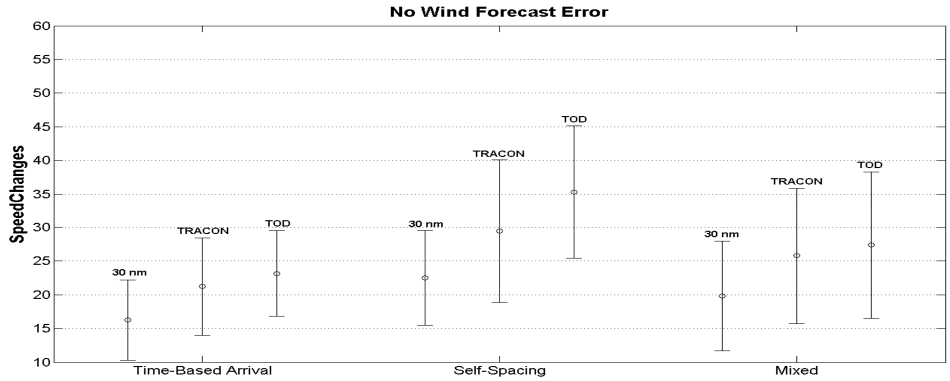

Figure 7: Arrival procedures speed change performance with no wind forecast error.

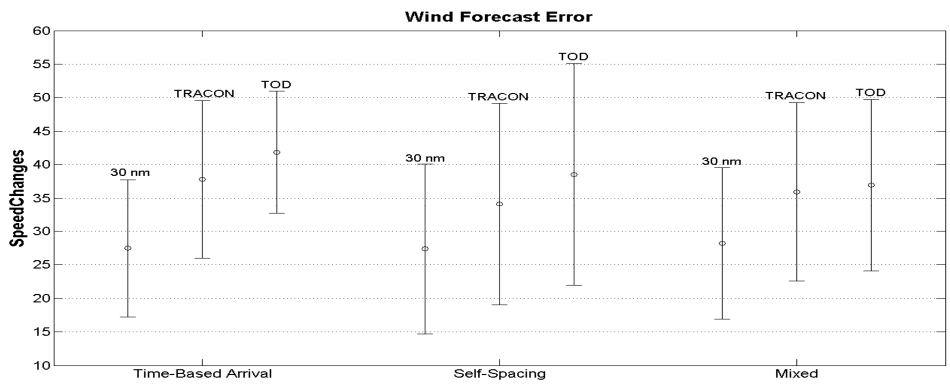

Figure 8: Arrival procedures speed change performance with wind forecast error.

Table 4: Arrival procedures' difference between maximum standard deviation spacing error with and without wind forecast error.

Procedures	*Maximum Mean Speed Changes with no Wind Forecast Error*	*Maximum Mean Speed Changes with 50% Wind Forecast Error*	*Percent Differences*	*Absolute Differences*
TBA	23.2	41.8	80.2%	18.6
SS	35.3	38.5	9.10%	3.20
Mixed	27.4	36.9	34.7%	9.5

D. Gap Creation Analysis

The creation of a gap in the arrival stream was introduced to observe the performance of each arrival procedure when a perturbation occurs. For this study, the gap was created by instituting an eighty second schedule delay to the twenty-fifth aircraft in the fifty aircraft arrival stream. The analysis of this experimental condition begins by observing how the delay affects the spacing capabilities of aircraft operating under both arrival procedures. To highlight the effects of the gap creation, the data before and after the gap were analyzed separately. Observing the percent difference in the standard deviation of each procedure's performance before and after the delay, shown in figure 9, indicates how much of an affect it had on each procedure's ability to achieve its spacing goal, see table 5. The percent difference in standard deviations for TBA and SS were 278% and 753% respectively. Although its percent difference was much larger, in this case, than that of TBA, the SS spacing performance with the created gap, at worst, was 109% greater than its performance without the gap, reference figures 3 and 9 at the TOD freeze horizon. Whereas TBA's spacing performance with gap creation was 306% greater than it was without the gap, comparison of figures 3 and 9 indicates that it was three times more difficult for TBA to achieve its spacing goal than it was for SS when a gap was created in the arrival stream.

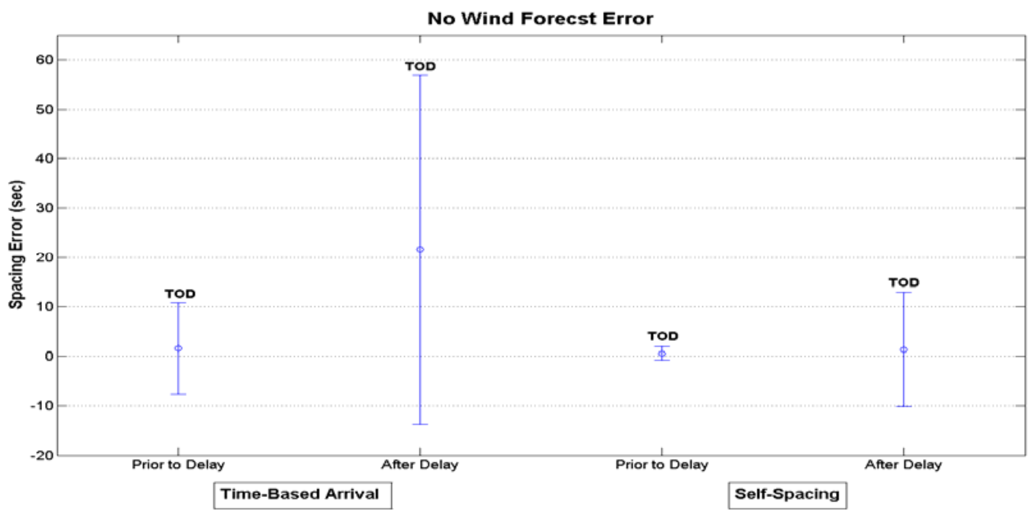

Figure 9: Gap creation arrival procedures spacing deviation performance with no wind forecast error.

Table 5: Arrival procedures' difference between maximum standard deviation spacing errors prior to and after gap creation.

Procedures	*Standard Deviations prior to Gap Creation*	*Standard Deviations after Gap Creation*	*Percent Differences*	*Absolute Differences*
TBA	9.35 sec	35.3 sec	278%	25.9 sec
SS	1.36 sec	11.6 sec	753%	10.2 sec

E. Runway Throughput Analysis

The maximum runway throughput is a function of the wake vortex categories and final approach speeds of the arriving traffic. This maximum value assumes that the aircraft can be delivered exactly at the minimum separation distance and that wake separation and not runway occupancy time is the limiting factor. The considerations, such as whether there is space on the airport surface to maneuver the aircraft after touchdown, gate availability and location, etc., are not included. As explained in reference 3 (Credeur, 1977), the actual achievable throughput is affected by the delivery precision of the aircraft. Assuming a normal distribution of delivery times around the assigned time, an adjustment is made to the desired spacing between aircraft so that only a small percentage of arrivals approach the minimum separation distance and require controller intervention to maintain safety. Credeur selected a 5% intervention rate resulting in an adjustment of $t_B = 1.65\,\sigma$. Intervention rates of 1% and 0.1% would result in $t_B = 2.33\,\sigma$ and $t_B = 3.10\,\sigma$ respectively. Given a set of spacing intervals in time and as a function of wake categories, the maximum runway throughput is

$$\lambda = \frac{1}{\bar{t}}$$

where $\bar{t}$ is the average inter-arrival time:

$$\bar{t} = \sum_{ij} t_{ij} p_i p_j$$

and t_{ij} is the spacing requirements matrix for an aircraft of wake category *i* following one of category *j*, and p_i is the percentage of the arrivals of wake category *i*. Assuming that the delivery uncertainty is independent of the aircraft's wake categories, the effect of the uncertainty is obtained by adding t_B to to $\bar{t}$.

The scenarios used in this study had 49% heavy, 37% B-757 and 15% large aircraft. The spacing matrix, in seconds, based on the slowest expected final approach speeds was:

$$SI = \begin{matrix} 145 & 145 & 109 \\ 163 & 132 & 103 \\ 181 & 145 & 115 \end{matrix}$$

For perfect delivery, this would give a throughput value $\lambda = 25$ aircraft/hr. Based on the standard deviation of all of the TBA and SS runs without wind forecast errors, the following achieved throughputs could be expected:

Table 6: Aircraft throughput per hour

Procedures	*5% Intervention*	*1% Intervention*	*0.1% Intervention*
TBA	23.7	23.2	22.6
SS	24.3	24.1	23.8

III. Conclusions

The purpose of this study was to explore the operational performances of two arrival procedures TBA, SS, and a mix of the two in a way that would distinguish one procedure from another at delivering aircraft to the runway. During the course of the study it was determined that TBA and SS performed to their expected strengths of scheduling and spacing respectively. When considering an equitable metric such as speed changes, which provide an indication of automation tool workload when achieving spacing or scheduling goals, SS separated itself from TBA and Mixed by having only a 9% increase in speed change as opposed to a 80% and 35% increase for TBA and Mixed respectively.

Unique to this study was the performance of the procedures when a gap was created in the arrival stream. An interesting observation of the performance difference between TBA and SS under this condition was the spacing metric. TBA's spacing performance during this condition compared to that of SS was in stark contrast to its spacing performance when operating under normal conditions. In normal conditions, with no wind forecast error, TBA's maximum standard deviation performance was within 43.0% of SS. Inserting a gap in the arrival stream and operating with no wind forecast error TBA's spacing performance both prior to and after the gap was now 586% and 204% within SS' performance under the same conditions. This indicated to us that this kind of perturbation affected TBA in a much more adverse way.

The performance of the Mixed procedure during spacing, scheduling, and speed change metrics was very surprising. Comparing TBA, SS, and Mixed procedure's maximum standard deviations shows that Mixed out performed TBA at speed changes and outperformed SS during both the scheduling and spacing metrics, which was very surprising. By besting SS in two of the three metrics of interest and TBA in one, it is certainly feasible to mix the two procedures in the same arrival stream.

There was no operational degradation in performance of TBA or SS at the metrics of interest where speed control responsibility is transferred from ATC to the aircraft. In areas where the procedures' operational concept was not biased toward the metric of interest, such as scheduling for SS and spacing for TBA, their performance levels were within a range that would distinguish one arrival procedures ability to deliver aircraft to the runway threshold under the metrics of interest.

Given that wind is the major culprit when aircraft miss an RTA or are unable to achieve a spacing goal, considering how both the procedures and Mixed perform when wind forecast error is introduced was very important. That being said, within the boundaries of this study the arrival procedures were able to deliver the aircraft to the runway without producing large deviations in spacing, scheduling, or speed changes. Therefore, the performance of TBA, SS, and Mixed were better than expected when operating with wind forecast error.

References

[1] Joint Planning and Development Office, "Concept of Operations for the Next Generation Air Transportation System" Version 2.0 13 June 2007.

[2] Joint Planning and Development Office, "Integrated Work Plan for the Next Generation Air Transportation System" Version 0.1 31 July 2007.

[3] Credeur, L., 1977, "Basic Analysis of Terminal Operation Benefits Resulting from Reduced Vortex Separation Minima", NASA TM-78624, Washington, DC, NASA.

[4] Abbott, T.S., 1991, "A Compensatory Algorithm for the Slow-Down Effect on Constant-Time-Separation Approaches", NASA TM-4285, Washington, DC, NASA.

[5] Williams, D.H., 1983, "Time-Based Self-Spacing Techniques Using Cockpit Display of Traffic Information During Approach to Landing in a Terminal Area Vectoring Environment", NASA TM-84601, Washington, DC, NASA.

[6] Abbott, T.S., 2002, "Speed Control Law for Precision Terminal Area In-Trail Self Spacing", NASA TM 2002-211742, Washington, DC, NASA.

[7] Osaguera-Lohr, R.M., Lohr, G.W., Abbott, T.S., Eischeid, T.M., 2002, "Evaluation Of Operational Procedures For Using A Time-Based Airborne Interarrival Spacing Tool", AIAA-2002-5824, Reston, VA, AIAA.

[8] Krishnamurthy, K., Barmore, B., Bussink, F.J.L., Weitz, L., Dahlene, L., 2005, Fast-Time Evaluations of Airborne Merging and Spacing in Terminal Arrival Operations, AIAA-2005-6143, Reston, VA, AIAA.

[9] Barmore, B.., Abbott, T.S., Capron, W.R., 2005, Evaluation of Airborne Precision spacing in a Human-in-the-Loop Experiment, AIAA-2005-7402, Reston, VA, AIAA.

[10] Barmore, B.E., Abbott, T.S, Krishnamurthy, K., 2004, Airborne-Managed Spacing in Multiple Arrival Streams, Proceedings of the 24th Congress of the International Council of Aeronautical Sciences, Stockholm, Sweden, ICAS Secretariat.

[11] Barmore, B., "Airborne Precision Spacing: A Trajectory-Based Approach to Improve Terminal Area Operations," 25th Digital Avionics Systems Conference, 15-19 Oct, 2006.

[12] Ostwald, P., "Impacts of ATC Related Maneuvers on Meeting A Required Time of Arrival" 25th Digital Avionics Systems Conference, 15-19 Oct, 2006.

[13] Prevot, T., Lee, P., Callantine, T., Smith, N., Everett, P., "Trajectory-Oriented Time-Based Arrival Operations: Results and Recommendations", 5th USA/Europe Air Traffic Management Research and Development Seminar, Budapest, June 2003.
[15] Hoekstra, J.M., 2001, "Designing For Safety: The Free Flight Air Traffic Management Concept", Doctoral Thesis, ISBN 90-806343-2-8, Delft University of Technology
[16] Bussink, F.J.L., N.A. Doble, B.E. Barmore, S. Singer, "A Fast-Time Simulation Environment for Airborne Merging and Spacing Research", 23rd Digital Avionics Systems Conference, Salt Lake City, 24-28 Oct, 2004.
[17] Nuic, A., "User Manual for the Base of Aircraft Data (BADA) Revision 3.6", Bretigny, France, Eurocontrol Experimental Center Report 2004-022, 2004. http://www.eurocontrol.fr/projects/bada/
[18] B. Barmore, T. Abbott, W. Capron, and B. Baxley, "Simulation results for airborne precision spacing along continuous descent arrivals," AIAA 2008-8931, Aviation Technology, Integration and Operations Conference, 14-19 Sept., Anchorage, 2008.