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Cueing System for Near-Term Implementation of Aircraft Noise Abatement Approach Procedures

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One of the main challenges to the implementation of advanced aircraft noise abatement approach procedures in the near future is the difficulty that pilots have managing the deceleration of aircraft in the presence of uncertainties in pilot response and weather conditions, and other system disturbances. In this paper, a new pilot cueing procedure that helps pilots manage the deceleration of aircraft and thereby achieve the target speed without additional aircraft automation is introduced. The cueing system, consisting of altitude/speed checkpoints ("gates") and a recommended flap schedule, was designed and evaluated in an experiment in which 15 active B767 pilots flew a desktop simulator using autoflight and flap controls. Results showed that the use of gates reduces target error to within 5 kt, which is comparable to that of electronic flap deployment cueing systems. The improved performance with gates and the positive response of the pilots to the concept suggests that gates are a viable technique that can be adapted for different types of approach procedures flown by aircraft equipped with old and new flight management systems. Furthermore, because the gates have the potential of enabling aircraft to fly consistent speed profiles, their implementation has the potential to enhance the controller's ability to predict aircraft trajectories and their future separation.

I. Introduction

IN A recent study, the Federal Aviation Administration (FAA) reported that the number of air travelers will grow by 50% by the year 2013 [1], and that traffic at 43 airports will reach or exceed the corresponding capacity by 2020, and, thus, these airports will need to build additional runways. Building runways to accommodate more traffic, however, will also inevitably increase the noise impact on communities surrounding airports, further exacerbating an already contentious airport noise problem. In the U.S., the FAA has taken a number of initiatives to reduce the aviation noise impact, starting with the Noise Control Act in 1976 followed by the Aviation Noise Abatement Policy in 2000 [2,3]. Among initiatives that have been developed to meet these goals in the near future, noise abatement approach procedures have been shown to be an effective means to reduce the noise impact on communities surrounding airports. These procedures reduce the noise impact by allowing aircraft to fly longer at higher altitudes, lower thrust levels, and lower drag than standard instrument landing system (ILS) approach procedures (see Fig. 1). These procedures were developed and flight tested by NASA as a part of the efforts to reduce fuel consumption during the fuel crisis in the 1970s [4,5]. The two most popular procedures were "delayed flap" and "decelerating" approaches. In a delayed flap approach, the extension of flaps and gear is delayed to reduce airframe noise, and the aircraft decelerates at idle power and is stabilized in the final approach configuration at 500 ft above the ground. The power, applied when the airspeed is within 15 kt of the reference speed, is used to stabilize the airspeed at the reference speed plus 5 kt. The decelerating approach is essentially the same as the delayed approach but differs in that the deceleration continues to touch down and the power remains idle throughout the approach. In these approaches, the points where the configuration changes depend on the aircraft's weight, the wind along the approach, and the angle of the ILS glide slope. In Europe, the notion of noise reduction through operational changes was a legacy of the historical push toward stabilized, continuous descent, nonprecision approaches. These approaches were pioneered in the 1980s and 1990s to get away from the dive and drive and reduce control flight into terrain. The notion that noise could be reduced came in later and is the basis for many current Euro-Control projects [6,7].

With the advent of advanced flight guidance and navigation technologies, in particular, area navigation systems (RNAV) and flight management systems (FMS), aircraft can fly flexible routes or trajectories created by a series of arbitrary reference points. Procedures that leverage these technologies are referred to as advanced noise abatement approach procedures (ANAAPs).

As an example of the effectiveness of such operational procedures, the ANAAP that was designed for the flight demonstration test at Louisville International Airport in the United States in 2002 [8] was shown to reduce the A-weighted peak noise level at seven locations along the flight track by 3.9 to 6.5 dBA. However, one of the main challenges to the implementation of these procedures in the near future is the mitigation of the effect of system uncertainty on performance. As an aircraft descends along the glide slope to the runway at idle thrust, its trajectory is highly dependent on its own performance characteristics, the variability in the wind conditions,

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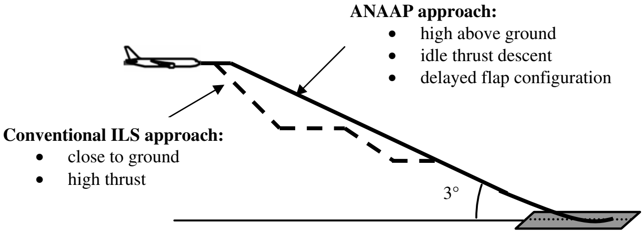

Fig. 1 An example of an ANAAP and a conventional ILS approach.

and on the variability in the response time of the pilot. The variability in wind field and in pilot response can adversely affect the trajectory of the aircraft, leading to unpredictability in the aircraft's speed profile, errors in the predicted time of arrival, and/or a missed approach (which results in a go-around and consequently more noise impact).

One way to mitigate the effect of pilot delay and atmospheric uncertainty is to provide pilots with cues to help them initiate the procedure and extend the flaps and gear in a timely manner. Researchers at the National Aerospace Laboratory in the Netherlands (NLR) have proposed that a flap/gear cue be displayed in the speed tape of the primary flight director (PFD) [9]. Similarly, researchers at NASA Langley have proposed the use of an energy indicator in conjunction with flap and gear annunciations as guidance events to help pilots determine when to extend the flap and gear [10]. Although these low-noise guidance tools and their cueing systems are viable solutions, they cannot be implemented in the near future because they require new automation capability that must be first certified and then included in the avionics suite of aircraft that are currently being or will be produced. They must also be retrofitted to aircraft that are already in operation. Because of the length and the significant cost of the avionics certification process and the equally significant cost of retrofitting avionics, it will take a relatively long time to achieve this critical mass, and the cost of implementation will likely prove to be financially burdensome.

In light of these considerations, there is an imperative to develop solutions that can be implemented in the near future while providing comparable performance to long-term, automated solutions. In this paper, the development and evaluation of a new pilot cueing system that can be implemented without adding automation is presented. Issues regarding the design of the cueing system, and the feasibility of its implementation, were investigated in a human factors experiment. The description of the experiment, along with the results and insights gained, is described in Sec. II. In Sec. III, conclusions and implications for the implementation of the cueing system in the near future are discussed.

II. Design and Experimental Evaluation of Gates

A. Conceiving the Cueing Systems

Without the help of a cueing system, pilots flying an ANAAP find it challenging when the aircraft is decelerating continuously to determine the flap schedule that is required to meet the target speed at a specific altitude. The challenge lies in the uncertainty in the speed profile of the aircraft and originates from two factors. The first is the inability of humans to estimate precisely, for a given flap setting, the aircraft's deceleration, which is nonlinear. The second is the pilot's forward projection of the flight progress based on an approximate deceleration may be inaccurate because the wind farther down along the flight path is not completely known, and the high workload during approach leaves the pilot with very little mental capacity and time to precisely compute the aircraft's deceleration.

To overcome these limitations, it is plausible to postulate that pilots may be better able to manage the deceleration if they are provided or updated with information indicating the progress of the deceleration. Given this hypothesis, the key question to be answered is what information and at what rate should the information be provided? In the limiting case when the rate of information can be updated and presented continuously, proposed solutions that require airborne automation such as the NASA Langley energy indicator with guidance events or the NLR's speed bug are feasible ways to implement this scheme. However, it is also important to determine if the information can be presented without automation and updated at a slower rate, and, yet still provide pilots with the information they need to manage the deceleration effectively. Such a strategy is consistent with the stabilized, continuous descent nonprecision approach procedures where pilots are able to stay close to the desired vertical flight path if they are provided with simple, discrete checkpoints as a feedback mechanism to correct for altitude deviation (see Fig. 2 for an example for runway 23R at Düsseldorf Airport in Germany).

These observations, and the underlying design principle, are the basis for a new cueing system that 1) helps the pilot mange the growth in uncertainty in the aircraft's speed profile by updating the target states; 2) mitigates the undesirable effects of pilot delay and errors in wind prediction; and 3) can be implemented in the near future and provide comparable performance to that of more automated solutions. To meet these objectives, a concept of using a series of gates or checkpoints, which are discrete points along the nominal speed profile, was proposed, investigated, and evaluated. As defined in this paper, each gate consists of an altitude and a speed. [The term "gate" as used in this paper is different than the term "approach gate" defined in the FAA Air Traffic Control (ATC) rulebook 7110.65, as the a point one mile outside the final approach fix. Unless noted

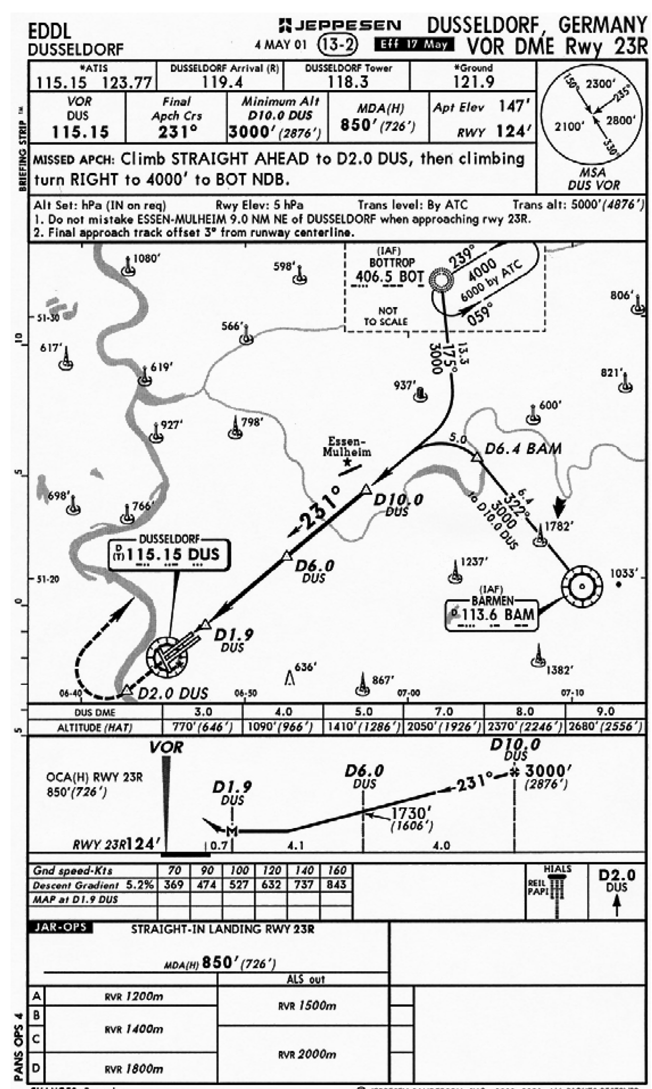

Fig. 2 Chart depicting very-high-frequency omnidirectional radio range DME approach to runway 23R at Dusseldorf Airport in Germany, which includes cross-checking of altitudes with DME distances because it is a nonprecision approach. (Reproduced with permission from Jeppesen Sanderson Inc.; not for navigation.)

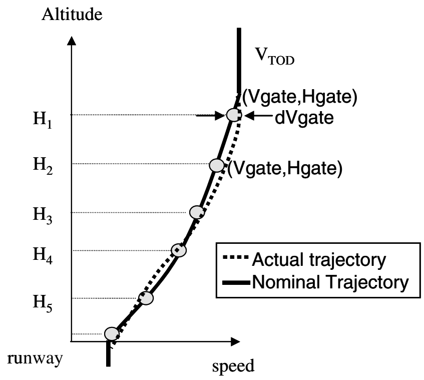

Fig. 3 Gates as a feedback mechanism.

otherwise, all gate speeds are indicated airspeeds.] The pilot would also be provided with a nominal flap schedule that allows the aircraft to achieve the target. Both the flap schedule and the gates are predetermined based on the nominal trajectory, nominal wind condition, and the aircraft's aerodynamic performance. The gates are used in conjunction with the nominal flap schedule to serve as a feedback mechanism to help the aircraft follow the desired speed profile. Specifically, each time the aircraft crosses a gate, the pilot determines the deviation in the aircraft's speed from the prescribed speed at the gate, and based on this deviation, the pilot makes small adjustments to the flap schedule so that the aircraft can meet the prescribed speed at the next gate and eventually the target speed (see Fig. 3). For example, when crossing a gate and the aircraft's speed is a few knots faster than desired, the pilot would extend the next flap a bit earlier than suggested, or conversely when the speed is a few knots lower than desired, the pilot would delay extending the next flap. The process of observing the speed deviation at a gate and making the adjustment to the flap schedule limits the growth in uncertainty of the speed. Because the gates and the flap schedule can be precomputed offline, they have the potential to be implemented without adding any onboard automation.

B. Objectives and Hypotheses

An exploratory, part-task simulator experiment was conducted to evaluate the utility of gates as a new cueing system, and to gain insights into how they may be used as a means to manage the deceleration of ANAAPs without adding cockpit automation. The setup and key results of this experiment are summarized in this section; interested readers are referred to [11] for further details.

The goal of the experiment was to examine the following questions:

1) What is the performance?

a) How well can pilots achieve the target when either 1) no information (neither a flap schedule nor gates were provided), or 2) just the flap schedule, or 3) gates and the flap schedule are provided?

b) How does target achievement change as the number of gates increases?

c) How does target achievement vary with wind uncertainty?

2) What are the considerations in gate design?

a) How many gates should be used?

b) Where should the gates be placed?

c) How far apart should the gates be?

3) What are the human factors issues?

a) Do the gates enhance a pilot's decision making? What are strategies that pilots would use when gates, or flap schedule, or nothing (neither a flap schedule nor gates were provided) is provided?

b) What are some feasible ways to present the gates and the flap schedule?

c) Do pilots accept the gates method? How many gates do pilots prefer?

4) What are the integration issues?

a) How should the gates be integrated into the cockpit?

b) What are some ways to design crew coordination and procedures for implementing gates?

In addition, it was hypothesized that for a maximum of three gates available in the experiment, the speed target error will vary from smallest to largest as follows:

1) with flap schedule (FS) and three gates, FS and two gates, FS and zero gate, and no FS;

2) with no wind uncertainty, with wind uncertainty.

C. Experiment Setup

1. Design of ANAAP and Gates

The ground track of the procedure, designed for runway 17R at Louisville Standiford International Airport (KSDF), is shown in Fig. 4. The altitude profile and the baseline speed profile are shown in Fig. 5. A target speed of 150 kt at the CDA07 waypoint was chosen. The constraints entered into the FMS are listed in Table 1.

To help pilots achieve the target speed of 150 kt at the waypoint CDA07, a gate cueing system was developed using the aircraft's drag polar model, the simulator, and an assumed no wind condition. The gate cueing cards system consisted of three gates placed at intervals of approximately 1000 ft along with a recommended flap schedule as shown in Table 2. Although adding more gates at smaller altitude intervals, such as every 500 ft, would provide pilots more information, the increase in the number of gates would increase the pilot workload and consequently become intrusive. The requirement that flap 5 be extended by WPD07 was introduced to ensure that as the aircraft descended from WPD07, it would have enough drag to decelerate, especially in tailwind conditions.

As shown in Table 2, the gates and the corresponding flap schedule were chosen so that after dialing down the autothrottle target speed at 6000 ft, pilots could estimate ahead to 5000 ft and determine how flap 15 should be adapted to meet 190 kt at 5000 ft. For example, in a tailwind, projecting and realizing that the speed would be higher than 190 kt at 5000 ft, the pilot would extend flap 15 before reaching

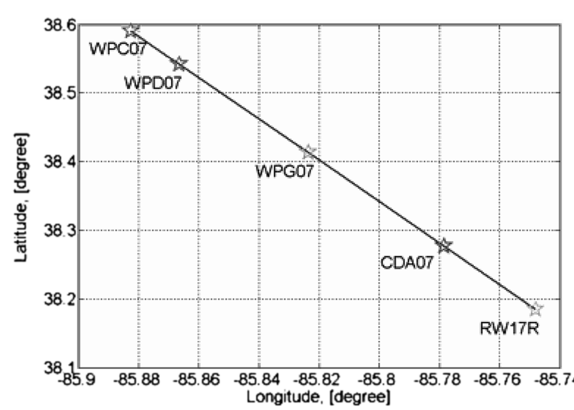

Fig. 4 Waypoint locations for flight track.

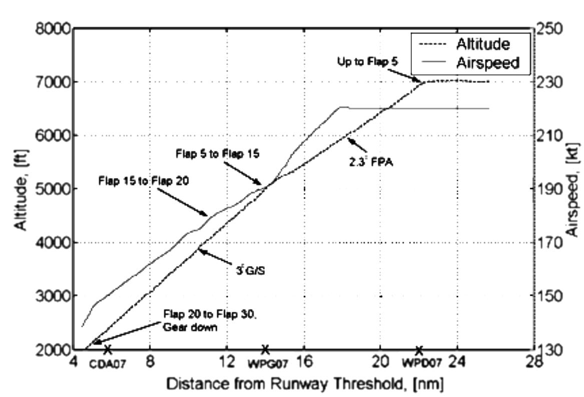

Fig. 5 Altitude and speed profiles.

Table 1 Speed and altitude constraints

Waypoint	Speed constraint	Altitude constraint
WPC07	At 220 kt	At 7000 ft
WPD07	At 220 kt	At 7000 ft
WPG07	No constraint	At 5030 ft
CDA07	At 150 kt	At 2350 ft

Table 2 Gates and recommended flap schedule

Gate (altitude/speed)	Recommended flap schedule
5000 ft/190 kt	Flap 5 by WPD07 (mandatory)
4140 ft/180 kt	Flap 15
3000 ft/160 kt	Flap 20

5000 ft and use the second gate at 4140 ft to determine when to extend flap 20. The last gate helps the pilot determine whether to extend flap 25. In addition, the pilot was not allowed to lower the landing gear, extend flap 30, use the speed brake, adjust the thrust, or retract an extended flap (some airlines discourage pilots retracting an extended flap because the retraction may incur mechanical jamming) before CDA07 (gear and flap 30 were normally extended at 2250 ft). These restrictions were chosen partly to reduce airframe noise and partly to focus the experiment on testing how well pilots can perform with a recommended flap schedule alone based on speed deviations at gates. These restrictions also meant that if the speed was fast as the aircraft approached CDA07, and flap 25 was already extended, there was nothing the pilot could do to reduce speed; similarly, if the speed was slow as the aircraft approached CDA07, the speed could not be increased because the pilot was not allowed to increase thrust. In the case that the speed reached the approach speed, the autothrottle would increase thrust to maintain the approach speed.

2. *Pilot Procedure with Gate Cueing Card*

An ANAAP continuous descent approach procedure using gates was developed as a variant of the conventional Standiford runway 17R ILS approach. Instructions were provided on a cue card as shown in the Fig. 6 example. This prototype card was designed to present information in a way that is easy to read and understand. High usability was achieved by placing information and instructions in "briefing boxes" that are organized in the Volpe chart format [12] (i.e., in a sequential order from left to right and top to bottom as usually seen in typical Jeppesen approach charts). As shown in Fig. 6, the card's first box contains information on the airport (KSDF), the runway (17R), the aircraft (B767-300), the aircraft gross weight (245,000 lbs), and the nominal wind condition (no wind) that the gates and the flap schedule were designed for. The second box, also called the CDA procedure box, contains instructions that trigger specific actions. Specifically, the first column specifies that by

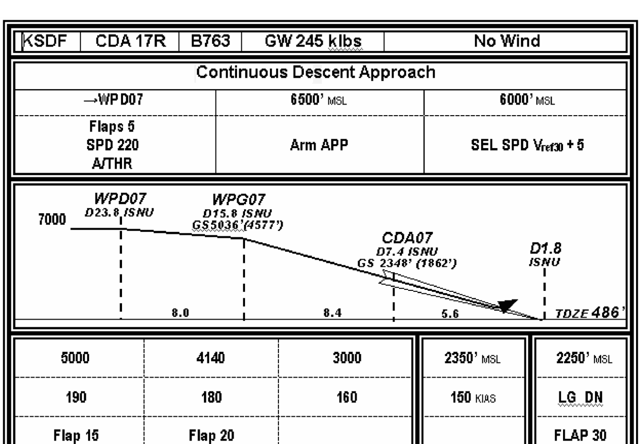

Fig. 6 A gate cueing card prototype.

WPD07, flap 5 be extended and the autothrottle set on. The second column specifies that at 6500 the approach (APP) mode be armed to capture the ILS. The third column specifies that at 6000 ft, the speed intervention (SI) mode be selected and the speed is dialed down to Vref30 + 5. The third box, also called the profile view box, contains information on the CDA waypoints' altitudes and distances from runway threshold. The last three boxes, read from left to right, contain the gates and the corresponding recommended flap schedule, the target speed of 150 kt at 2350 ft (CDA07 waypoint), and the instructions to lower the gear and extend flap 30 at 2250 ft.

3. *Independent Variables*

The two independent variables (IV) in the experiment design are the feedback mechanism, which has four treatments, and the uncertainty in wind, which has three treatments.

1) Feedback mechanism:

a) No flap schedule and no gates (NFS-0G): no flap schedule and gate information available, thus the pilot has to determine a flap schedule to decelerate the speed to 150 kt.

b) Flap schedule without gates (FS-0G): only the recommended schedule based on the no wind condition was provided.

c) Flap schedule with two gates (FS-2G): two gates, at 5000 and 3000 ft, were provided with the recommended flap schedule.

d) Flap schedule with three gates (FS-3G): all three gates at 5000, 4140, and 3000 ft were provided with the recommended flap schedule.

2) Wind uncertainty:

a) No wind (NW).

b) Tailwind (TW): constant magnitude of 15 kt at 7000 ft, and thereafter the magnitude decreases linearly to 10 kt at the surface.

c) Headwind (HW): constant magnitude of 15 kt at 7000 ft, and thereafter the magnitude decreases linearly to 10 kt at the surface.

The test matrix was a 3×4 repeated-measures design in which each subject flew all 12 experimental conditions. To mitigate fatigue and boredom, subjects were frequently given breaks and 10 airports with different field elevations and final approach tracks were used. To offset ordering effects, counterbalance trial runs, and reduce learning effects, the trials were first randomized and then selected so that the following two criteria were met: 1) the first and last six trial runs each contains two HW, two TW, and two NW approaches; and 2) trial runs 1–4, 5–8, and 9–12, each contain one NFS-0G, one FS-0G, one FS-2G, and one FS-3G cue.

4. *Measurements and Performance Metrics*

Two types of measurement were taken: aircraft states and subjective questionnaires at the completion of the experiment. Aircraft states included time, position (range, latitude, longitude, and altitude), indicated airspeed, appendages (flap, gear, speed brake), thrust (N1), and wind (speed and direction).

Based on the measurement of aircraft states, the following performance metrics were computed: the absolute value of the aircraft's speed deviation at CDAWP (CDA waypoint), the pilots' adaptation to the flap schedule, and the flight time variation at the CDA gate.

Two types of subjective questionnaires were used: open-ended questions and closed questions with a 7-point rating scale. These questionnaires contained questions regarding pilots' strategy of using speed deviations at gates to adapt the flap schedule; pilots' preference on number, distance between, and placement of gates; pilots' acceptance of the gate cueing system as a method to manage speed and deceleration; pilot suggestions on the implementation of the presentation of and crew coordination with gates.

5. *Simulator Facility*

The simulator facility is shown in Fig. 7. The hardware consisted of a desktop Pentium III computer with two 20 in. monitors. In addition, a mouse, a keyboard, and an Aerosoft Australia's 747 mode control panel were used to control the aircraft functions. The simulation software consisted of the Microsoft Flight Simulator

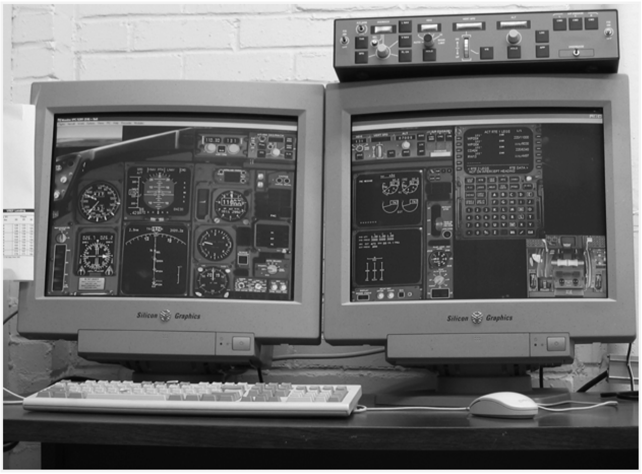

Fig. 7 Simulator displays and MCP.

(MFS) 2002 Professional Edition and the 767 Pilot in Command (PIC). The MFS is a PC simulation game that provides aircraft, virtual cockpits, airports, scenery, air traffic control, and weather. The 767 PIC is MFS add-on software, which emulates the dynamics of a B767-300 and provides a reasonably accurate representation of the actual B767 cockpit and its FMS.

To ensure that the fidelity of the aircraft dynamics was sufficient for the evaluation of target achievement, the simulator was validated in two different ways. The first was by flying the simulator and comparing its performance to flight recorder data from actual flight tests conducted using UPS B767 aircraft. The parameters used in the comparison include glide performance (e.g., vertical speed versus airspeed in different configuration settings), dynamics response (e.g., due to configuration changes), and flaps extension times. The comparison showed that the 767 PIC closely mimics the behavior of an actual B767 for the procedure developed for the experiment. The second validation entailed having an active B767 captain fly the simulator and comment on any differences in the performance of the simulator's deceleration at different flap settings to that of the actual B767. The captain did not detect any differences. The captain also commented that for the trajectory designed for this experiment, the simulator's FMS performed similarly to that of the actual B767's FMS. This is also another important validation because in this experiment the automation was on supervisory control (pilots did not fly manually) so adequate realism of the FMS was desirable.

6. *Protocol*

The experiment was conducted at the International Center for Air Transportation (ICAT) at the Massachusetts Institute of Technology (MIT). Each subject took approximately 3.5 h to complete the experiment. At the beginning of the experiment, subjects were given a briefing, which included information on the motivations for the experiment, the pilot procedures, and the gate cueing cards. Subjects were then trained with three to four approaches with no wind, tailwind, and headwind. The training criteria include proficiency with using and understanding the rationale behind the gates on the gate cueing cards, and understanding that their performance would be scored on how close they were to the target speed of 150 kt when the aircraft was at CDAWP. Subjects were also told that there was no preference for them to try to be on the fast or slow side of 150 kt. In addition, subjects were also given the following instructions:

1) Follow the provided pilot procedure. If a procedure error is made, the approach will be rerun.

2) All trial runs have the same aircraft weight of 245,000 lbs.

3) If speed reaches approach speed (Vref30 + 5) before the CDA gate, the autothrottle will increase thrust to maintain speed. No penalty point will be counted for this.

4) Once flap 25 is extended, if the aircraft is still fast approaching the CDA gate, then the subject must "live with it."

5) Observe and comply with placard flap speeds and minimum maneuver speeds.

6) For experimental purposes, dialing mode control panel (MCP) speed to Vref30 + 5 at flap 5 is acceptable (some airlines' policy prohibits dialing down speed below the minimum maneuvering speed of the current flap setting), and extending flap 25 before gear is lowered is acceptable and does not trigger an audible ground warning alarm (the alarm would go off in an actual B767).

7) Do not use the speed brake.

8) Do not retract an extended flap.

9) Do not manually reduce thrust to idle or turn off autothrottle.

10) Do not arm approach before the descent waypoint (WPD07).

11) Do not extend the gear before the CDA gate (CDA07) or extend flap 30 before the gear is lowered.

These instructions and training were designed to help ensure that all subjects received the same training and therefore would use the gates the same way because it is likely that every subject has a predilection on how the flap extension and deceleration should be managed. All subjects met the training criteria and had no trouble using the simulator or adhering to the procedures. One important contributing factor to this was that at the time of the experiment, the subjects had, on average, last flown a B767 four days before participating in the experiment (the minimum was two hours and the maximum was two weeks).

7. *Subjects*

Only active B767 airline pilots with Air Transport Pilot rating were recruited for the experiment because of their familiarity with the B767 deceleration performance, especially the aircraft decelerations at different flap settings. All 15 participants—two chief pilots, seven captains, and six first officers—were volunteers from Alitalia Airlines, American Airlines, United Parcel Service, United Airlines, and US Airways. Their flight experience ranged from 4500 to 19,800 hours, with a mean of 10,456 hours, and their age ranged from 31 to 56 years of age, with a mean of 43.75. Eleven pilots reported having previously flown noise abatement approach procedures, in particular, the continuous descent approach procedure at London Heathrow Airport in the U.K. and other airports in Europe.

D. Experiment Results

The statistical analysis package SPSS 10.0 for Windows was used to perform analysis of variance (ANOVA) to determine the significance of the effects of the experiment factors. The results presented in this section mainly focus on the target achievement performance, the considerations in gates design, and the integration of gates into the cockpit. The results on human factors issues, summarized in Secs. II and III, are elaborated in [7].

1. *Performance in Terms of Achieving 150 kt at CDAWP*

Because the primary objective of this experiment was to determine how close pilots could get to the speed of 150 kt at CDAWP with no preference to being on the fast or slow side of 150, the performance metric was defined as the absolute speed deviation between the aircraft's speed and 150 kt at CDAWP.

a. Effect of Feedback Mechanism (FM). The boxplots of the speeds at CDAWP are shown in Fig. 8. (In a boxplot, the median of the data set is denoted by the centerline in the box; the lower and upper quartiles are denoted by the outer edges of the box; and the extreme values, representing the potential outliers, are the ends of the whisker lines extending from the interquartile range.) In all wind conditions, the speeds at CDAWP tend to get closer to the target speed, 150 kt, as the FM level increases. In addition, when there was no wind, the speed appears to evenly scatter around 150 kt. In the tailwind conditions, the speed tends to be above 150 kt because the tailwind tends to cause the aircraft to arrive at CDAWP earlier and with a higher groundspeed (and vice versa is true for the headwind conditions).

The means of the speed deviations at CDAWP and the one standard error (SE) of the corresponding means are shown in Fig. 9 for each wind condition and in Fig. 10 for all wind conditions. As shown in Fig. 9, increasing the number of gates improved the

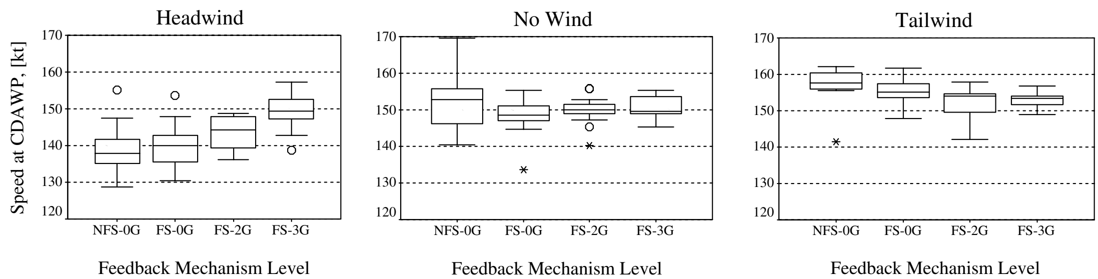

Fig. 8 Boxplots of the speeds at CDAWP. ○ and * symbols denote outliers.

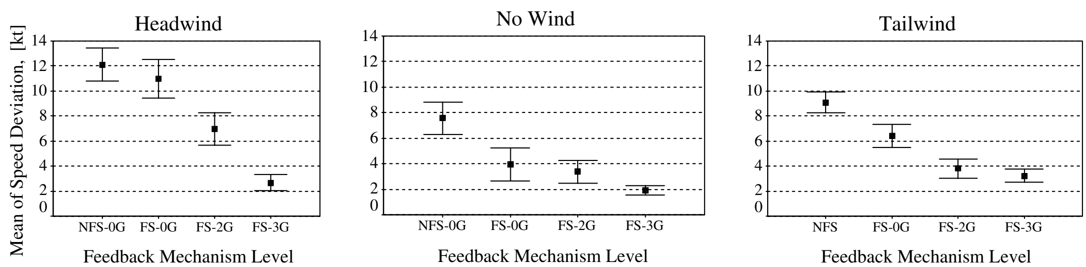

Fig. 9 Feedback mechanism effect on the speed at CDAWP for each wind condition. Mean of speed deviation with ±1SE for each wind condition.

achievement of 150 kt at CDAWP in all wind conditions. The improvement is approximately two knots for every additional gate. Pairwise comparisons for the main effect of FM showed that there were significant main effects for all treatments ($p < 0.006$ for FS-0G vs NFS; $p < 4e-7$ for FS-2G vs NFS; $p < 1e-8$ for FS-3G vs NFS; $p < 0.004$ for FS-2G vs FS-0G; $p < 1e-5$ for FS-3G vs FS-0G; $p < 0.003$ for FS-3G vs FS-2G). These effects suggest that regardless of the wind condition, subjects' performance improved significantly as the flap schedule and more gates were provided.

b. Effect of Wind. The means of the speed deviations at CDAWP and the one SE of the means in each wind condition with all FMs combined are shown in Fig. 10. There were two significant main effects ($p < 4e-4$ for HW vs NW and $p < .012$ for HW vs TW). These effects suggest that regardless of the FM provided, achieving the target speed was the most difficult in the HW condition. This result was consistent with the comment by a number of pilots that "misjudging the aircraft's deceleration in headwind approaches leads to early flap extensions, which in turn, causes the aircraft to slow down too much before reaching the target speed." When this happens, recovering the speed through delaying flap extensions is usually not possible because 1) the flap extension can only be delayed until the aircraft reaches the minimum maneuvering speed of the current flap setting, at which point the next flap must be extended, and this extension consequently increases the deceleration; 2) the headwind resulted in a slower groundspeed (i.e., the aircraft arrived at CDAWP later than nominal) and pilots had difficulty applying a slow enough deceleration to compensate; and 3) the use of the thrust was not allowed.

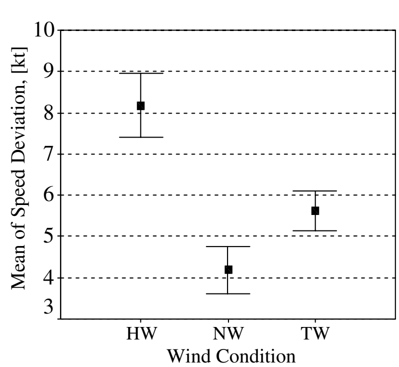

Fig. 10 Feedback mechanism effect on the speed at CDAWP. Mean of speed deviation with ±1SE for each wind condition with all FMs combined.

In tailwind and no wind approaches, pilots commented that if the aircraft appeared to be fast as it approached CDAWP due to inadequate deceleration with flaps 15 and 20, then they would extend flap 25 to increase the deceleration. Thus, having the discretion to use flap 25 allowed the pilots to prevent the aircraft from reaching CDAWP too fast as evidenced in the lower mean of the speed deviation in TW and NW conditions than in the HW condition (see Fig. 10).

2. *Pilot Strategies*

The experiment results also provided many important insights into the issues concerning the human factors aspects of gates implementation. First, as anticipated, the ways in which the pilots adapted the flap schedule based on their observation at the gates were intuitive. When the aircraft was or was projected to be fast at a gate, the pilots tended to extend the flap early to increase the deceleration and vice versa. In tailwind approaches, the pilots tended to extend the flaps early and used the speed deviation at each gate to ensure that the aircraft's speed profile would not deviate too far from the nominal speed profile. In headwind approaches, pilots recognized the additional deceleration accompanying the headwind and delayed the flap extensions.

Second, the strategy that some pilots developed to handle the case when neither a nominal flap schedule nor gates were available could be extremely valuable for training new pilots on how to use gates. In particular, if pilots could approximate the amount of speed that must be bled off for every 1000 ft (i.e., by dividing the total speed that must be lost over the decelerating segment by the altitude range in that segment) and keep track of this amount by thinking up virtual gates and using them to make projections of the flight progress along with the gates, then the target achievement would improve. This strategy can be used in training to provide pilots with a method to project the deceleration and a big picture of how the speed should be managed in the presence of wind uncertainty.

3. *Pilot Feedback on Gates Design of Gates and the Implementation of Gates*

Consistent with the performance at CDAWP, all pilots indicated that they preferred to have at least two gates. More than half the pilots felt that having three gates was optimal because three gates provided them a checkpoint every 1000 ft to monitor their progress, and having more or less than three gates would require them to pay more attention, and consequently, either increase their workload or make the extra gate information unhelpful. On the other hand, some pilots preferred to have more than three gates because they believed that more gates allowed them to check the speed profile progress more often and made it easier to "fine-tune" the flap schedule. All pilots commented that placing the gates every 1000 ft was acceptable. This result is also consistent with their comment that they were able to detect, at 1000 ft above the target, whether the aircraft could reach 150 kt at the target.

Overall there was high acceptance of the idea of gates by the pilots and agreement that gates would be useful as a means of managing the deceleration of aircraft and thereby meeting speed targets for noise abatement approach procedures. Eleven pilots commented that using the gates and the recommended flap schedule does not compromise safety and gives them targets to cross-check and manage the aircraft's deceleration, just as in the technique that they use to cross-check altitudes at specific distance-measuring equipment (DME) in nonprecision approaches. Six pilots commented that the crews in general would "appreciate" the gates because it means that the crews would have more flexibility and be more active in managing the profile of the aircraft's speed whereas in the current operation, they reduce the aircraft's speed by stepping down in increments as dictated by controllers. Furthermore, taking pride in their ability to achieve targets, they felt that they would welcome the challenge of managing an aircraft decelerating at idle thrust.

Despite the high acceptance of the implementation of the gates, three pilots cautioned that providing too much information (such as too many gates) or too little information (such as not enough gates) could unnecessarily increase workload, especially with fatigued crews. Thus the right balance of information is the key to operate safely and to keep the pilot inside the decision-making loop. They reiterated that providing gates every 1000 ft is a viable way to achieve the balance.

Another potential problem that pilots were asked to comment on was the presence of a strong headwind or tailwind or a shift in the wind direction (i.e., from a headwind to a tailwind or vice versa) during the decelerating segment. The pilots commented that there are several measures that could be taken to cope with these circumstances. First, three pilots thought that the speed must be carefully monitored so that it would not decrease below the Vref. Airbus's FMS and Boeing's FMS have different protection schemes for this. Airbus's FMS logic would not allow the speed to decrease below Vref, whereas Boeing's FMS logic may allow the speed to decrease below Vref, depending on the type of FMS. In addition, five other pilots mentioned that another important factor is the company's/airline's rules, which specify the values at which flaps should be extended. Second, seven pilots commented that additional noise impact must be accepted to accommodate strong winds or shifts in the wind's direction. For instance, they thought that the crew could use power to maintain the aircraft's speed in a strong headwind or use speed brake to slow down the aircraft in a strong tailwind. Moreover, the gate cueing card should also contain disclaimers that state that the presence of strong winds may require early or delayed flap configuration. Third, four pilots felt that crews in general can be trained to be flexible with the procedure and mindful that the gates are designed for a nominal wind condition and that the crews should anticipate to compensate for wind changes. Although these measures are potentially viable, they deserve further investigation given the benefit of achieving a more fuel-efficient and quieter approach of ANAAPs.

Although the experiment did not have many features of the actual cockpit environment, pilots' opinion on the potential workload that they might experience with gates in actual operation were solicited. A majority of the pilots felt that the task of managing the aircraft's deceleration and achieving 150 kt at CDAWP becomes easier when they were provided with more gates. Ten pilots explained that they did not have to perform the mental "gymnastics" when they were provided with gates every 1000 ft. Many pilots thought that, because the cross-checking of the speeds and altitudes of the gates was similar to that of performing altitude and distance checks in a nonprecision approach, the learning curve was not high.

The pilots' opinion was also solicited on a number of issues that must be carefully addressed in designing the protocol and procedures for crew coordination when the gates are implemented. First, as gates can potentially take a lot of attention of the pilot flying (PF), the pilot monitoring (PM) must be aware of the situation and keep the PF informed about the "big picture" of the operation. To accommodate this, six pilots suggested that the crew coordination should be similar to that of a nonprecision approach: the PM monitors all aspects of the approach and makes callouts to the PF about the deviations at the gates and the parameters of the next gate while the PF calls out his actions (such as request for flap extension) when making adjustments to keep the aircraft as close as possible to the gates. This task allocation keeps the PF's attention on flying and monitoring the approach rather than dividing attention between the procedure and flying. For example, it was suggested that "dialogue boxes" should be designed and incorporated in the training manuals. The dialogue should prescribe a script of confirmation between the PF and the PM on the gate/altitude/speed of the aircraft, and the PM's verbalization that includes positive or negative speed deviations such as "10 miles plus 2000 minus 15" or "10 miles on profile." Three pilots also suggested that a briefing between the PF and the PM is essential and should be part of the training.

The second issue centered on storing and using gates information in the FMS. Three pilots suggested that gates should be stored as waypoints that define a procedure in the FMS database. When used this way, they believed that crews could use the gates as references and allow the FMS to calculate the altitude and speed, with the target at the outer marker as a mandatory speed. In low traffic, the crews would fly the FMS profile, and in high traffic, the crews would use the published procedure to have all the aircraft following a consistent speed profile.

These suggestions are worthwhile of further investigation that would provide additional insights into the way pilots manage the aircraft deceleration.

E. Discussion of Experiment Results

It was anticipated that providing pilots with a nominal flap schedule and gates would improve their ability to achieve a target speed in the presence of wind uncertainty and would help them manage the deceleration by observing the speed deviation at the gates and making the necessary adjustments to the nominal flap schedule. The target achievement results supported these hypotheses. In particular, it was found that adding an additional gate would improve the speed target achievement by 2 kt, and providing a gate at every 1000 ft with a flap schedule reduces target error to within 5 kn. This achievement is comparable to those reported in [9] where an electronic flap deployment cueing system was used.

It was also interesting to note that while the headwind condition was generally thought of as the easiest wind condition to fly an ANAAP because of the additional deceleration accompanying the headwind, the results in this experiment did not corroborate this notion. On the contrary, the headwind approaches were particularly difficult for pilots because extending the flaps early (due to misjudging the deceleration) could slow down the aircraft too fast. This in turn made the aircraft reach the target speed before the target altitude and consequently increased the noise impact because additional thrust must be engaged to maintain the approach speed. Given that in existing practice most of the approaches are into a headwind, this finding highlights the importance of having a cueing system such as gates to avoid early thrust engagement.

It was important to note that if the pilot could achieve the speed target at the CDAWP with only the gates and the recommended flap schedule, then the pilot would be able to perform the same task better with the speed brake and the thrust. This is because the speed brake gives the pilot the additional control authority to reduce the speed when the aircraft is fast while the thrust gives the pilot the control authority to increase the speed when the aircraft is slow. Thus, the results obtained in this experiment (using the flaps alone) represent the performance with conservative control authority.

Placing the gates every 1000 ft along the decelerating segment of the profile seemed to strike the balance between providing adequate checkpoints for target achievement and maintaining the workload at a manageable level. Moreover, the 1000 ft spacing of gates matched the pilots' ability to make projection of the deceleration within

1000 ft. This result was also consistent with the pilot's evenly divided opinions on whether the first gates were as useful as the last gates and implied that the gates should be evenly placed and spread out instead of concentrating in the beginning or the end of the profile.

There was some concern that the gates might not be effective because the pilots would be inundated with processing gates information and making projection of the flight progress. However, the pilots indicated that they had seen the gates in a different form (via nonprecision approaches), that the gates were very useful, and that the gates would not increase workload if they were designed appropriately. The prototype gates cueing card used in the experiment was a contributing factor for the high pilot acceptance, and if a crew coordination protocol could be developed for training and actual operations as suggested by the pilots, then the gates would enhance the pilot decision-making process.

Although these results were obtained with the overarching goal of using the gates as a means of helping pilots manage the aircraft's deceleration, it should be noted that because this experiment was a preliminary, proof-of-concept study focusing on the feasibility of gates, the experiment was conducted in a controlled laboratory environment that lacked many actual operation elements such as crew coordination, traffic, controller-pilot communications, and weather. In addition, the subjects participating in the experiment were volunteers and were very enthusiastic about the prospect of implementing noise abatement approach procedures. Therefore, the results may be biased toward pilots favoring new pilot cueing systems for ANAAPs.

III. Conclusions

The markedly improved performance with gates and the positive response of the pilots to the idea of gates suggest that gates are a viable concept that deserves further investigation. An important issue to consider in this investigation is the adaptability of the technique developed in this work to different approach procedures, especially those flown by aircraft equipped with an old FMS. The ANAAP technique used in this experiment—FMS RNAV, transitioning to ILS guidance when on the glide slope—could be adapted, for example, for nonprecision approach FMS procedures used by many airlines today. In these procedures, pilots fly the published nonprecision approach procedure to the published minimum descent altitude (MDA) but using FMS VNAV guidance all the way. This is typically done by flying to a waypoint entered at the runway threshold at the touchdown zone plus 50 ft and setting the MDA in the altitude window, and using vertical speed mode adjustments to follow the VNAV football guidance. In the existing operation, these procedures are flown by aircraft equipped with FMS installed before the required navigation performance (RNP) transition. Given that these older FMS aircraft will be in service for many more years, this adaptation will be a key factor accelerating the implementation of ANAAP in the near future. For aircraft equipped with navigational sensors that meet RNP requirements, the procedure developed in this work could be a vertical guidance (APV) approach flown via the wide area augmentation system (WAAS) down to the decision height (DH).

Another important issue is the implementation and validation of the developed ANAAP CDA gate cockpit procedure. Although this procedure could be validated and implemented relatively quickly without requiring elaborate changes and recertification of aircraft autoflight and FMS hardware or software, the principal requirements that must be addressed are the design of the gliding flight approach paths appropriate for aircraft type, landing gross weight, and wind category, the creation of corresponding families of cue cards, integration with current ATC procedures, and appropriate crew training.

Finally, it also appears that the gates would be an enabling factor to achieve significant noise reduction in heavy traffic flows without adding additional aircraft automation. The key to achieving this lies in the pilot's ability to use gates to adjust the nominal flap schedule and maintain the desired speed profile in response to changing operating conditions. Thus, it is plausible to hypothesize that when aircraft can maintain the desired speed profile, the predictability in the separation of the aircraft would increase. Analogous to the way that pilots currently fly the final several miles of nonprecision approaches using constant angle of descent techniques with the aircraft in landing configuration, pilots flying ANAAPs can use similar techniques while in gliding flight earlier in the approach to reduce the noise footprint. One way to test this hypothesis is to conduct a controller-in-the-loop study with actual crew coordination in the cockpit, controller-pilot communications, traffic, and weather. Such a study would also provide insights into the feasibility of the gates method, determine the predictive capabilities of controllers, and determine whether changes in the roles of the pilot and controller might enable better overall system performance.

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