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Methodology for Optimizing Parameters of Noise-Abatement Approach Procedures

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Noise-abatement approach procedures reduce the noise impact on communities surrounding airports by enabling aircraft to stay at higher altitudes for longer and to descend at lower power than standard approach procedures. A design challenge of these procedures is the selection of the procedure parameters that minimize the adverse impact of pilot delay and wind uncertainty. In this paper, a methodology developed to determine the optimum design parameters is presented. The methodology includes the following steps: 1) formulating the procedure's parameters as strategic and tactical control variables; 2) conducting a simulator-based human-factor experiment to obtain models of pilot delay in extending flaps/gear in different levels of turbulence; 3) using the pilot-delay models and the parameter formulation to perform a Monte Carlo simulation to resolve the conflicting objectives of reducing noise and increasing probability of target achievement; and 4) determining the feasibility parameter space in different wind conditions. Simulation results showed that the flap schedule has to be designed to get the aircraft to its final approach speed at a target altitude that is 50 ft higher than the required altitude when there is no turbulence and 200 ft higher than the required altitude when there is turbulence. Moreover, when the wind uncertainty is large, the effectiveness of the procedure is reduced because the initiation altitude must be reduced. A discussion on the implementation of strategic and tactical control variables is also provided.

Nomenclature

H	=	altitude
H_F	=	target altitude
H_I	=	altitude at which thrust is reduced to idle
H_{TOD}	=	altitude at which the aircraft begins uninterrupted descent to the runway
$\dot{h}$	=	aircraft vertical speed
K	=	configuration (flap and gear) schedule
T_{idle}	=	idle thrust
U_{flap}	=	speed at which the flap is extended
$U_{\mathrm{rud,ail,el}}$	=	control surfaces such as the rudder, aileron, and elevator
V_F	=	target speed at a specific distance (defined by γ and H_F before landing on the runway occurs)
V_{TOD}	=	speed at the top of descent
v	=	aircraft speed
$\dot{v}$	=	aircraft deceleration
$\mathbf{W}$	=	wind vector as a function of altitude
x	=	aircraft position
γ	=	flight path angle

I. Introduction

WHEN commercial aircraft use the instrument landing system (ILS), the primary landing aid for commercial aircraft, for landing guidance, they are required to intercept the glide slope [(GS), most frequently 3 deg] from below (see the left side of Fig. 1) and consequently spend considerable time maneuvering at low altitudes. In addition, because high-lift devices such as flaps must be used when operating at low speeds, and because airlines often train their crews to lower the landing gear early to ensure that the final approach configuration is achieved well before the point on the GS at which their aircraft is required to be in the final approach configuration, the engine thrust must be increased to overcome the increased drag and thereby maintain the final approach speed. In combination, the close proximity to the ground, the high thrust, and the induced airframe noise due to the extended flaps and gears produces significant noise impact on those communities along the approach path.

Low-altitude maneuvering may be eliminated by using the vertical navigation (VNAV) mode of the flight management system (FMS) and waypoints with appropriate altitude and speed restrictions to create idle or low-power flight paths that aircraft follow, without vectoring or leveling off, from a high altitude to the ILS GS. Approach procedures that leverage these technologies to reduce noise are referred to as advanced noise-abatement approach procedures (ANAAPs). In the example ANAAP shown on the right side of Fig. 1, an aircraft would intercept a 3-deg flight path that is aligned with the ILS GS, at 7000 ft. After initially descending at a constant speed, the aircraft would then decelerate at idle thrust along the 3-deg flight path and along the upper portion of the GS; the pilots would initiate the transition to the autopilot approach (APP) mode when the aircraft is safely within the coverage areas of the both the localizer (LOC) and GS. Upon achieving the final approach speed, at or above the point on the GS at which the aircraft is required to be in its final approach configuration, the aircraft would continue the descent to the runway at its final approach speed and thrust. It is important to note that the example ANAAP is only one of many that can be created using the capabilities of the FMS, but that in all such procedures, the noise reductions are achieved by flying at higher altitudes and at lower thrust for longer than current standard approach procedures and by delaying flaps and gear extension. The noise benefits of ANAAPs have been demonstrated in a number of simulator studies [1–4] and in a recent field experiment [5] in which

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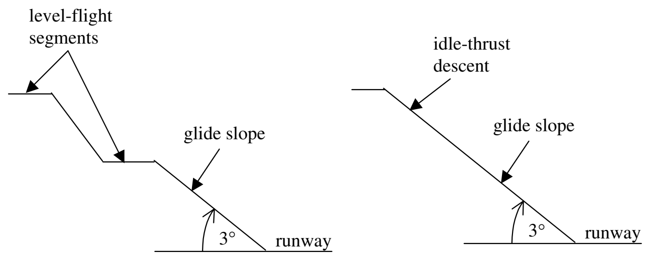

Fig. 1 Standard ILS approach procedure (left), advanced noise-abatement approach procedure (right).

reductions of 3 to 6 dB in peak A-weighted noise levels were observed (A-weighted adjusts for the fact that human hearing is less sensitive to low and high frequencies than to midrange frequencies of sound).

To fully implement the example ANAAP (or any ANAAP) in heavy traffic, it is necessary to overcome the effects of system uncertainties on aircraft performance. The trajectory of an aircraft that descends at idle thrust to the point on the GS at which it is required to be in its final approach configuration is highly dependent on the aircraft's own performance characteristics, the prevailing wind conditions, and on the response times of its pilots. In particular, variability in the wind field and in pilot-response times can significantly affect the trajectory of the aircraft, leading to unpredictability in the aircraft's true airspeed and ground-speed profiles, errors in the predicted time of arrival, and/or missed approaches (which result in a go-around and consequently more noise impact). Thus, one design challenge is the selection of procedure parameters that minimize the adverse impact of uncertainties in atmospheric conditions and pilot-response times.

In this paper, a methodology to determine such optimum ANAAP parameters is presented. The context for this presentation is the example ANAAP in Fig. 1. However, the methodology itself is generally applicable to the design of any ANAAP. That being said, the ANAAP depicted in Fig. 1 will be the basis for all subsequent analyses and discussions in this paper, which is organized as follows. Definitions of the ANAAP parameters and the sources of uncertainties are presented in Sec. II. In Sec. III, the design and analysis of the example ANAAP is discussed in the context of treating certain parameters as strategic and tactical control variables. With this treatment, sets of feasible flap schedules are first determined, based on given values of the strategic control variables, and are then used to study the impact on target achievement of delays in pilot responses and wind uncertainties. A discussion on the implementation of strategic and tactical control variables is also provided. A summary of the paper and conclusions are presented in Sec. IV.

II. Definition and Key Drivers for Procedure Design

A. Definition of Procedure Parameters

A detailed profile of the example ANAAP is shown in Fig. 2 , in which V_F and H_F denote the final approach speed and the corresponding altitude at which it should be achieved, and γ is nominally 3 deg. This definition is based on the assumption that after passing the top of the descent (TOD), the aircraft descends along a flight path that is aligned with the GS. However, it may be desirable to design the vertical flight path to have several segments with different flight path angles in some cases, for example, using a vertical segment that is shallower than the angle of the GS to provide additional drag for an aerodynamically efficient aircraft or to accommodate a strong tailwind.

Flaps are devices that help increase the lift coefficient of the wing at slow speeds during landing (and takeoff). Each flap setting corresponds to an increase in the lift and drag coefficient. For instance, a Boeing 767-300 has seven flap settings: 0, 1, 5, 15, 20, 25, and 30. The higher the flap setting, the higher the lift and drag coefficients.

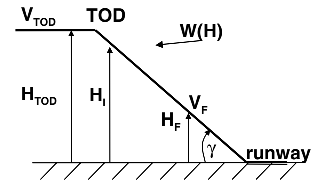

Fig. 2 Procedure definition.

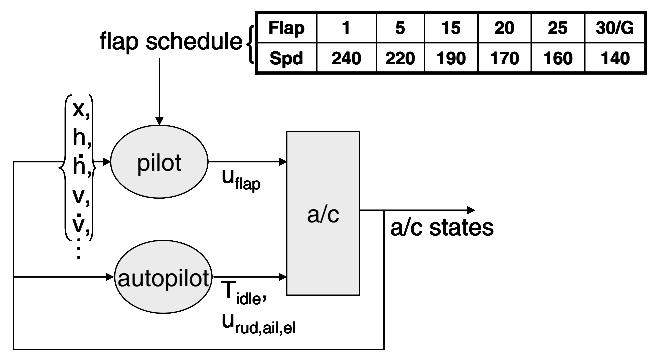

Fig. 3 Pilots control loop during the deceleration segment of ANAAP.

As shown in Fig. 2, the aircraft commences the procedure at V_{TOD} and H_{TOD} and maintains a level flight segment until it reaches the top of descent. At this point, the aircraft starts its uninterrupted descent to the runway, maintaining V_{TOD} until altitude H_I, when the thrust is reduced to idle. From this point onward, the aircraft decelerates to V_F, and if V_F is reached before H_F, thrust is engaged to maintain V_F.

As shown in Fig. 3, the pilots' primary tasks during an ANAAP (in addition to other standard tasks) are to

1) Extend the flaps at the speeds specified in the given flap schedule. At a given flap setting, the speed takes on a value between the maximum and minimum maneuvering speeds (see Table 1 for an example) and is chosen to ensure that the aircraft will reach the target speed and altitude. Wind corrections are typically added to the speed.

2) Determine when to and then extend the flaps, based on their observations of the aircraft's states such as position, altitude, vertical speed, velocity, and deceleration. The typical procedure for extending the flaps is that on command, via call out by the pilot flying (PF), the pilot monitoring (PM) observes and verifies the relevant aircraft states and executes the order. For instance, upon receiving a flap-extension request, the PM observes the flap speed limit and moves the flap handle to the requested position. The autopilot and the FMS manage all of the aircraft's flight-control functions (e.g., idle thrust and control surfaces such as the rudder, aileron, and elevator) in both the lateral and vertical domains by providing thrust and steering targets (e.g., pitch, pitch rate, and roll) to the thrust management computer (which controls thrust) and flight control computer (which controls rudder, aileron, and elevator movements).

Speed-brake usage was considered as a possible solution [6] to normalize the idle-descent-rate differences among aircraft with different aerodynamic efficiency. However, this solution was dismissed because the speed brake is intended to function as a compensatory device for unforeseen environmental (wind) and traffic conditions. Using speed brakes also proves to be undesirable

Table 1 B757 minimum maneuvering and maximum placard speeds

Flap	MMS	MPS
0	205	
1	185	240
5	165	220
15	145	210
20	145	195
25	130	190
30	130	162

from a human factors point of view, because pilots may leave the speed brake extended when not needed. To preclude this, many airlines require that the PF keep a hand on the speed brake whenever it is used in flight [7]. Other reasons that make the usage of speed brakes undesirable include additional airframe noise and vibration in the cabin, which would be uncomfortable for the passengers.

B. Key Drivers for Procedure Design

1. *Objectives of System Stakeholders*

Although any flight procedure must satisfy the constraints imposed by the structure of the airspace, air traffic control (ATC) procedures, crew procedures, and airline policies, an ANAAP must also be synthesized to achieve the goals set by three main stakeholders: the residential community surrounding airports, the pilots, and the air traffic control operators. The primary goal of the residential community is to reduce the noise impact. Unlike in a standard ILS approach in which the aircraft has to fly at low altitudes and speeds for extended periods, aircraft flying the ANAAP depicted in Fig. 2 begin their descent to the runway at a higher altitude, typically 6000 or 7000 ft, and decelerate during the descent at idle thrust from a V_{TOD}, typically at 210 to 250 kt, to their final approach speed. ATC regulations require that aircraft fly at 250 kt or less below 10,000 ft, and many airlines set 240 kt as a speed limit by policy. The Honeywell flight management computer (FMC) VNAV descent logic decelerates the aircraft to have 240 kt as the default maximum speed below 10,000 ft by default so that there is a 10-kt buffer to the legally required maximum. However, at least one other FMC uses 250 kt as the default. Because the average speed in an ANAAP is higher than in a standard ILS approach, the flaps and gear are extended later. The combination of flying at higher altitudes, lower thrust for longer than ILS approach procedures, and delaying flaps and gear extension significantly reduces the noise impact.

The objectives of the pilots include ensuring adequate safety margins, providing sufficient margins to cope with wind uncertainty, and providing operationally feasible and stable flight control. These objectives can be achieved by judiciously choosing the values of the ANAAP parameters. The parameter H_I provides a means for pilots or controllers to delay the idle thrust reduction to compensate for higher than predicted headwind, and the parameters H_{TOD} and V_{TOD} can be adapted to compensate for tailwind conditions. The parameters H_{TOD}, V_{TOD}, and H_I can be selected to allow aircraft to operate within their operational envelope and have a sufficient time to decelerate to the target altitude and speed. The flight path angle can be chosen to match that of the GS of the existing ILS facility (this typically varies between 2.5 and 3.1 deg). It is also important to note that although a fixed flight-path angle, such as three deg, can be designed for both straight-in and curved approaches, the aircraft dissipates more energy in a curved approach, because the banking for turning requires a higher angle of attack and produces additional induced drag. To compensate for the additional energy dissipation in a curved approach, changes in one or a combination of these design parameters is required, for example, a lower value of H_I would be used in a curved approach, because the deceleration during the descent would be greater.

The objectives of the air traffic controllers include ensuring predictability and controllability in aircraft speed, horizontal and vertical flight path, and time of arrival. As defined in Fig. 2, the aircraft is assigned a target speed at a target altitude above the runway. The target altitude typically corresponds to the last point along the descent path at which the controller would issue commands to the aircraft. The speed and altitude targets act as a mechanism to ensure predictability in the aircraft trajectory in several ways. First, the speed target helps maintain separation by ensuring that the aircraft will decelerate neither so fast that it will impede the trailing aircraft nor so slowly that it will catch up with the leading aircraft. If either case occurs, the separation between aircraft may decrease below the required wake-turbulence-separation minimum, forcing the aircraft to break off the approach. (The wake-turbulence-separation requirements of aircraft in different weight classes and relative positions in a queue are documented in [8]) The target speed and altitude also ensure that the speed is reduced to a range that allows the aircraft to satisfy the requirement that they be fully established and stabilized in the landing configuration by 1000 ft above ground level (AGL) for instrument approaches; otherwise a go-around is compulsory for most airlines. This requirement is critical because "rushed" approaches are the leading cause of approach and landing accidents, including controlled flight into terrain [9]. Thus, in practice, commercial airline pilots conducting instrument approaches seek to be within ± 5 kt of the final approach speed at 1,000 ft: the stabilized and fully configured (SFC) criteria. It is important to note that in the analysis throughout this paper, the target speed and altitude will not necessarily be the SFC criteria. Rather, they will be the speed and altitude that ensure that the SFC criteria are met.

The parameters V_{TOD}, H_{TOD}, and H_I and the configuration schedule can be integrated into different methods that controllers use to sequence and separate aircraft. However, the level of integration highly depends on the communication, navigation, and surveillance capability of current and future ATC environments and will be discussed in more detail in Sec. III.

2. *Sources of System Uncertainty*

One of the most significant sources of uncertainty is wind-prediction error [10]. In actual operation, the wind field at the surface is known, but the wind field along the descent path is not completely known. Although the magnitude and direction of the wind at the current location can be determined instantaneously by the onboard inertial navigation system (INS), the wind information further along the trajectory is based on a mixture of real and modeled data, is anywhere between 0 and 6 h old, and is only available every 3000 ft. The resulting wind-prediction error would decrease the effectiveness of an ANAAP. For instance, in the idle descent from H_I to H_F, a stronger than predicted headwind would result in the aircraft slowing down to V_F sooner than desired. This in turn would require a nonidle thrust level to maintain V_F, thereby increasing the noise impact.

Another significant source of uncertainty is the variability and latency in the response of pilots. In standard approaches, this uncertainty is not a significant factor in the trajectory of an aircraft, because flaps and gear are used primarily to change the aerodynamic characteristics of the aircraft as it transitions from one speed range to another. In fact, many airlines' operating manuals, such as that of American Airlines [7], state that, "Flaps provide for operation at lower speeds and should not be used as a drag device to reduce speed" and that "Speed reduction should be made using speed brakes in lieu of flaps." Additionally, the Boeing Company, a major aircraft manufacturer, suggests, "Avoid using the landing gear for increased drag. This minimizes passenger discomfort and increases gear door life [11]". Consistent with these guidelines, pilots generally do not use flaps and gear as the primary means of slowing the aircraft down. In contrast, the performance of an aircraft flying the example ANAAP depends critically on the ability of pilots to extend the flaps and gear at the right moments to meet the speed and altitude targets while decelerating at idle thrust.

Pilot conformance to ATC commands is another source of uncertainty. In the existing operating paradigm, pilots have the discretion, although within a reasonable limit, of determining when to execute the maneuver (or procedure) for which they have been given clearance. For instance, during an approach, upon receiving the ATC clearance to descend to a lower altitude, the pilot may not initiate the descent immediately (unless ATC indicates that immediate action is required), because the command is not generally time-critical in nature. In contrast, pilots performing an ANAAP need to promptly initiate the descent if the aircraft is to achieve the desired altitude, speed, and thrust profile during the descent and thereby fully achieve the environmental benefits of the procedure.

Finally, another important source of uncertainty is the variability in the aerodynamic and engine performance of aircraft of identical type. For example, two B767-300s may have different deceleration performance for a number of reasons. One reason is that the aircraft may have different weights due to factors such as the number of the passengers on the aircraft, the weight of the cargo, the weight of the fuel, and the aircraft's zero-fuel weight. For a given aircraft type operating at a particular airport, it is possible to quantify the distribution of the weight and thus incorporate it in the design. Other reasons are that the aircraft's engines are different due to the fact that different manufacturers produced them or that the aircraft's airframe shapes are not the same because of dissimilarities resulting from the assembly or manufacturing processes.

III. Managing Uncertainty Through Strategic and Tactical Control

The ANAAP parameters defined in Sec. II provide a basis for design and analysis. In this section, design and analysis are discussed within the context of treating certain ANAAP parameters as tactical and strategic control variables.

As defined in this paper, a control system has both strategic and tactical control variables. The strategic control variable purports to move the system's states to the desired values within a gross range or resolution, so that the tactical control variable can then drive the states to the desired values within the required, often smaller, range or resolution. For example, on the beams of a physician's mechanical scale, the strategic control variable is the 50-lb (course or strategic) graduation, whereas the tactical control variable is the 0.2-lb (fine or tactical) graduation. To measure a person's weight, the V-shaped bearing on the 50-lb graduation scale is first adjusted to obtain the weight within 50 lb of the actual weight, the bearing on the 0.2-lb graduation is then adjusted to determine the weight in 0.2-lb resolution.

A. Tactical and Strategic Control Formulation

The ability of an aircraft to achieve the speed and altitude targets depends on the drag of the aircraft in each flap setting. However, the range of speeds over which the aircraft may be operated in a given flap setting is limited. Each flap setting has an upper speed limit, referred to as the maximum placard speed (MPS), and a lower speed limit, referred to as the minimum maneuver speed (MMS). The upper limit prevents structural damage and the lower prevents aerodynamic stall. Thus, for a given wind condition and an H_{TOD}, the design problem centers on choosing a feasible set of ANAAP parameters (see Fig. 2 for reference) consisting of H_I, V_{TOD}, and K that enable the aircraft to achieve the speed and altitude targets. Because one of these three parameters can be determined if the other two are specified, there are three ways to express the relationship among them, as shown in Fig. 4:

1) $K = f(V_{\mathrm{TOD}}, H_I)$, where K is determined by fixing V_{TOD} and H_I, which means that for a given choice of V_{TOD} and H_I, different flap schedules can be used to achieve the target.

2) $V_{\mathrm{TOD}} = f(H_I, K)$, where V_{TOD} is determined by fixing H_I and K, which means that for a given choice of H_I and K, different V_{TOD} can be designed to achieve the target.

3) $H_I = f(V_{\mathrm{TOD}}, K)$, where H_I is defined by fixing V_{TOD} and K, which means that for a given choice of V_{TOD} and K, different H_I can be designed to achieve the target.

Although all three relationships may be used in the procedure design, it makes the most sense to use the first relationship, because the parameters V_{TOD} and H_I can only be modified before the top of descent and the point at which the thrust is reduced to idle, respectively, after which they cannot be adjusted to account for any perturbations that may occur during the descent. On the other hand, the flap schedule can be modified many times during the descent, because there are up to six flap settings, with overlapping ranges of speed over which they may be selected. Thus, the flap schedule can be used to account for wind and pilot-response uncertainty. Moreover, in their radio voice communications to pilots, controllers issue commands with even numbers, typically in multiples of 1000 ft for altitude commands and in multiples of 10 kt for speed commands. Thus, V_{TOD} and H_I can be treated as strategic control variables and the flap schedule can be treated as a tactical control variable.

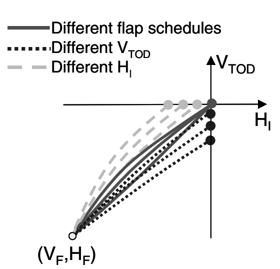

Fig. 4 Speed vs altitude profiles for different flaps schedules, different V_{TOD} and different H_I.

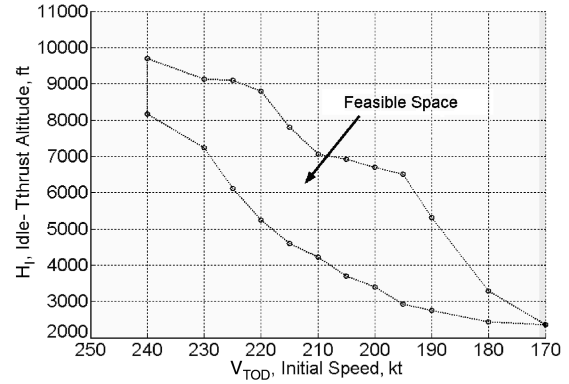

Fig. 5 Envelope of H_I and V_{TOD} that provides feasible flap schedules.

Based on these observations, the goal when designing the example ANAAP is to determine the envelope (or set) of H_I and V_{TOD} that will guarantee a feasible flap schedule. To demonstrate how this can be done, such an envelope was developed for a generic B757, for which a fast-time simulation was readily available. The envelope developed by varying H_I and V_{TOD} for a B757 weighing 180,000 lb and operating in no wind is shown in Fig. 5. The target is 170 kt at 2350 ft. The MPS and MMS for each flap setting are shown in Table 1. As shown in Fig. 5, the parameter space of H_I and V_{TOD}, in which feasible flap schedules exist, is inside the area bounded by the MMS and MPS lines. V_{TOD} is capped at 240 kt to be consistent with the speed limit below 10,000 ft, as implemented in the Honeywell FMC that is used in the B757. For every pair of H_I and V_{TOD} inside this area, except along the MMS and MPS lines, there exist an infinite number of flap schedules, because mathematically, $K = f(V_{\mathrm{TOD}}, H_I)$ and K is not unique for a given pair of V_{TOD} and H_I.

It is also interesting to note the general trend (shown in Fig. 5) of increasing V_{TOD} with increasing H_I for the example ANAAP. This occurs because increasing H_I lengthens the deceleration distance from H_I to H_F, thereby requiring the aircraft to start out at a higher initial speed V_{TOD} so that it has adequate speed differential relative to the target. In other words, if H_I is high and V_{TOD} is small, the aircraft will decelerate to the target speed before reaching the target altitude. Conversely, if H_I is small and V_{TOD} is large, the aircraft will reach the target altitude at a speed higher than the target speed.

Another important consideration in choosing V_{TOD} is the aerodynamic performance of the aircraft. For many aerodynamically efficient aircraft, the aircraft may accelerate during the descent if the flap is not extended to the first or second position before the aircraft commences the uninterrupted descent to the runway, due to insufficient drag. For instance, the B757 in its clean configuration (flap zero) would accelerate if V_{TOD} is above 210 kt. Therefore, the flap 1 position must be extended before the descent. However, this would result in increased airframe noise.

With V_{TOD} and H_I as strategic control parameters, the pilot can make adjustments to the flap schedule to cope with uncertainty due to unforeseen changes in the wind and differences between the actual wind profile and the wind profile being used by the FMS, or uncertainty in their own future responses. The result, as illustrated in Fig. 5, is that the parameter space that the designer of an ANAAP has to work with is much smaller than that of conventional approaches, in which the aircraft can be initialized virtually anywhere and still achieve the target speed, because pilots have the ability to use the speed brake or the thrust to slow down or speed up the aircraft as often as needed. This implies that speed and altitude targets can only be achieved in the presence of uncertainties by both understanding how the feasible space changes and through the use of cueing systems that help pilots perform tactical control, because it is difficult for pilots to determine the optimum adjustments to the nominal flap schedule. The development of cueing systems for implementation with and without adding additional automation in the cockpit is discussed by Ho [12].

B. Strategic Control Design for Robustness to Pilot Uncertainty

1. *Modeling Pilot-Response Time*

The pilot can be early or late in initiating the procedure at the TOD, in reducing the thrust to idle at H_I, or in extending the gear and flaps throughout the descent. As depicted in Fig. 6, when the pilot is early (for example, due to their desire to "stay ahead of the aircraft"), the aircraft reaches the final approach speed above the required altitude, and the thrust must be increased from idle to maintain speed. The resulting nonidle thrust level increases the noise impact. On the other hand, when the pilot is late, the aircraft reaches the final approach speed below the required altitude and may either be too fast to land or not fully stabilized and configured as it should. Either of these results would significantly increase the probability of a missed approach. Thus, it is important to model the variability in pilot response and thereby develop strategies to mitigate any adverse impact this variability might have on aircraft performance.

A model of pilot-response time was built using data from a related experimental study that was conducted in the NASA Ames Research Center Crew-Vehicle Systems Research Facility (CVSRF) B747-400 level-D full-motion flight simulator in 2002 [3]. The arrival procedure flown in that experiment was a straight-in ILS approach to runway 17R at the Louisville International Airport (KSDF). The vertical profile of the arrival noise-abatement procedure is shown in Fig. 7. As shown, the aircraft intercepted the GS from a higher than typical altitude and followed it to the runway. During the descent, the engine thrust was set to idle and the aircraft decelerated continuously to the speed restriction at the final approach fix. The continuous deceleration was achieved through the increased drag of the extended flaps and gear.

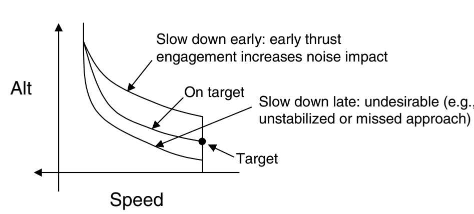

Fig. 6 Speed profiles for late, on target, and early pilot response.

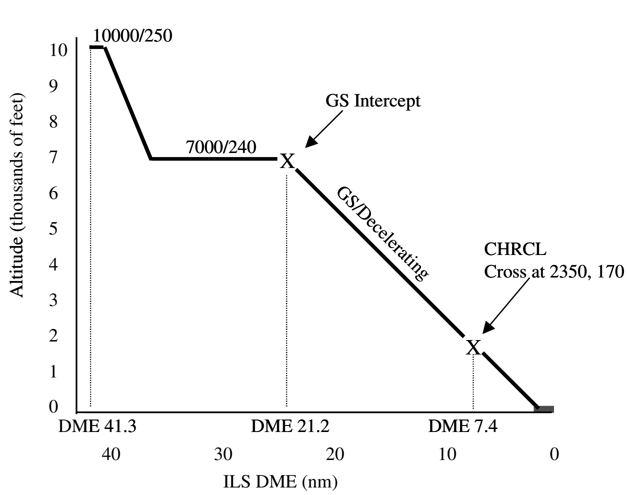

Fig. 7 KSDF ILS DME 17R arrival profile.

The approach began with the aircraft at 250 kt, 10,000 ft, and 41.3 distance measuring equipment (DME). The pilots were given an ATC clearance to descend to 7000 ft and maintain 240 kt until they intercepted the GS, at which point they were cleared for the approach and landing to runway 17R. The pilot procedure included 1) engaging the VNAV and lateral navigation (LNAV) modes, 2) arming the LOC button before intercepting the localizer, and 3) pushing the speed-intervention button and dialing in the final approach speed of 170 kt at the specified altitude at which the thrust was scheduled to be reduced to idle. This put the thrust at idle and left the thrust at idle for as long as the aircraft could maintain the desired descent angle. The pilot controlled the deceleration by extending the flaps and gear according to a flap/gear-extension schedule. The eight subjects were airline captains and first officers. The pilot-delay time, defined as the time the pilots initiated the thrust reduction or the flaps and gear extensions, minus the time the aircraft reached the specified altitude or speed at which each action was scheduled to occur, was recorded. With this definition, a negative delay time indicates that the pilot was early.

The histogram and the curve-fitted probability distributions (solid lines) of the pilot-delay time are shown in Figs. 8–10 for three cases:

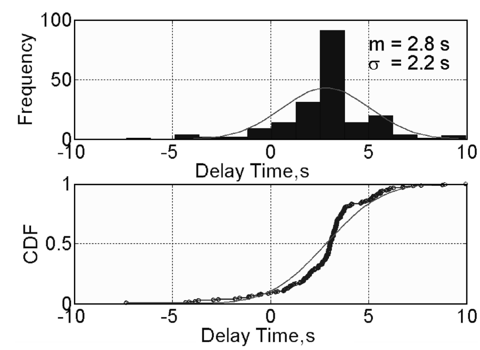

Fig. 8 Histogram and fitted cumulative distribution function (CDF) of pilot-delay time (PF cues PM to extend flaps/gear).

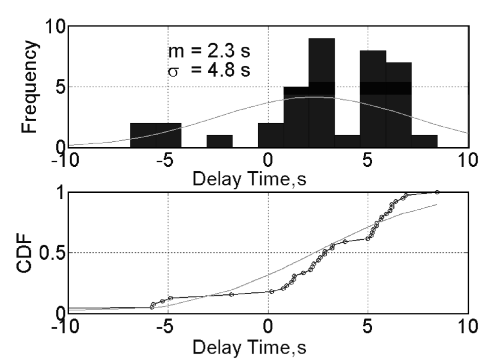

Fig. 9 Histogram and fitted CDF of pilot-delay time (PF cues PM to extend flaps/gear) in 25% turbulence.

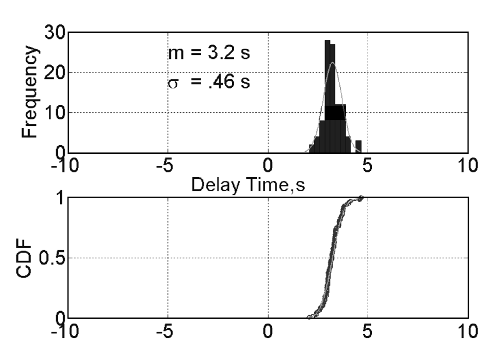

Fig. 10 Histogram and fitted CDF of pilot-delay time (PF extends flaps/gear himself).

1) The pilot flying cues the pilot monitoring to extend the flaps or gear.

2) The PF cues the PM to extend the flaps or gear during 25% rate of turbulence. The magnitude of the wind speed is 25% of the maximum turbulent speed. The components of the maximum turbulent speed are $u = .742$ m/s, $v = 43.54$ m/s, $w = 9.038$ m/s, yaw is 0 rad/s, and roll is 0.0027 rad/s. The method of generating turbulence is proprietary to CAE.

3) The PM extends the flaps or gear themselves.

Comparing the cases without turbulence, the variance of the pilot-response time is smaller when the PF extends the flaps or gear themselves. This makes sense because there are fewer opportunities for diversions from the task when the PF does not have to cue (via call out) the PM to move the flap and gear handles. That being said, it is common practice in the cockpit of commercial aircraft for the PM to extend the flaps and gear based on cues provided by the PF, because this process provides some measure of feedback to the crew. The presence of turbulence increases the variance of the pilot-response time as expected, because the pilots typically have to extend greater effort coping with the random variations in speed and altitude caused by turbulence.

Finally, the positive delay time suggests that pilots tend to be on the late side. This delay likely originates from the time it takes for the PM and the PF to perform the mental and physical tasks of monitoring the instruments, comparing the target in the predetermined flap/gear schedule with aircraft states, issuing and coordinating the commands, and moving the flap/gear handles to the requested position.

The fact that the pilots tend to be late implies that in the design of a procedure, the procedure parameters must be chosen to account for this delay. As shown in Fig. 6, the aircraft reaches the final approach speed (140 kt) at an altitude below the required altitude (1000 ft) when the pilots respond slowly. To mitigate the effect of pilot delay, the flap schedule must be designed with a target altitude that is higher than the required altitude to ensure that the final approach speed is achieved at or just above the required altitude.

2. *Performance Tradeoff: Noise Reduction and Target Achievement*

The discussion in the previous section suggests that the goal of achieving the final approach speed at the required altitude (in the presence of pilot delay) is in conflict with the goal of reducing the noise impact. Thus, the design goal must be to determine the best combination of the parameters that minimize the noise impact while maximizing the probability that the aircraft will be in the required speed window at 1000 ft.

To explore this tradeoff, Monte Carlo simulation studies were performed using a high-fidelity B737-300 numeric simulation (the simulator is described by Ho [12]). Given that the procedures for monitoring the instruments and performing the flap changes are similar for aircraft types ranging from heavy aircraft (e.g., B737) to small aircraft (e.g., B747), the pilot-response models obtained in this experiment with the B747-400 could be considered aircraft-independent. The models can also be used for fast-time simulation with other aircraft types. In the simulation, the aircraft was initialized to fly at a constant altitude of 7000 ft H_{TOD} at 220 kt V_{TOD}. Upon intercepting the GS (which was assumed to extend to an altitude of 7000 ft), the aircraft held its speed at V_{TOD} until reaching a specified H_I and followed a predetermined flap schedule that was designed to allow it to reach its final approach speed at a specific target altitude. Although there were many feasible flap schedules that would allow the aircraft to reach the final approach speed at the target altitude, the one that resulted in the smallest airframe noise was chosen (i.e., by choosing the speeds to extend the flaps as close to the minimum maneuvering speeds as possible, especially for higher flap settings). The weight of the aircraft was set to 114,000 lb and the landing flap was set to 30 deg. Using these values, a V_{ref} of 135 kt and an approach speed of 140 kt ($V_{\mathrm{ref}} + 5$ kt) were obtained. The SFC conditions (final approach speed V_F and required altitude H_F) were therefore 140 kt and 1000 ft, respectively. The corresponding speed window was between 135 and 145 kt. The pilot-response time was assumed to follow the normal distribution, shown in Fig. 8, with a mean of 2.8 s and a standard deviation of 2.2 s. It is important to note that this pilot-response model does not take into account the adjustments that pilots would make if they think the aircraft is too fast or too slow. For instance, if the pilots think that the speed of the aircraft is high, they may extend the flap early; if they think that the speed of the aircraft is low, they delay extending the flap. Because these adjustments are not included in the pilot-response model, the response times used in the simulation are conservative. They randomly take on positive and negative values regardless of whether the aircraft's speed is high or low.

The trade space was spanned by varying the target altitude and the idle-thrust altitude. Specifically, a set of flap schedules was designed for the aircraft to reach 140 kt at target altitudes ranging from 900 to 1300 ft. The idle-thrust altitude was independently varied between 4000 and 7000 ft, in 1000-ft increments. For each combination of the parameters (target altitude and idle-thrust altitude), the simulation was repeatedly run (approximately 400 times) until the results converged.

The probability that the aircraft speed is inside the speed window of 135 and 145 kt at the required altitude of 1000 ft (reaches the "required speed window") is shown in Figure 11, along with the reduction in size of the 55-dB contour area (a measure of noise savings that are achieved). As shown in the figure, the aircraft misses the speed window (probability of zero) if the target altitude is below 900 ft, and the aircraft is guaranteed to be in the speed window (probability of one) if the target altitude is at or above 1050 ft. An interesting feature of the probability curves is that for a given target altitude, the difference in the probability appears to be small for different values of H_I. This indicates that the choice of H_I has little impact on our ability to construct a flap schedule, which results in the aircraft being in the speed window at the required altitude. Rather, it is the target altitude relative to the required altitude that has the greatest impact. The small differences between the probability curves also indicate some measure of insensitivity to delay in reducing the thrust to idle, further supporting the notion of H_I as a strategic variable.

The average noise savings in the physical size of the 55-dB contour area in square miles for different values of H_I is also shown in Fig. 11. The 55-dB contour area, a standard aviation noise metric used to indicate the area (and also population) exposed to the 55-dB noise level, was computed by using the Integrated Noise Model (version 6.0) developed by the Federal Aviation Administration for evaluating aircraft noise impacts in the vicinity of airports. The noise savings is defined as the reduction in the noise-impacted area if a noise-abatement approach procedure were used instead of a typical ILS approach procedure. The trend in the figure indicates that as the target altitude increases, the average noise savings decreases. This trend occurs because increasing the target altitude results in the aircraft reaching 140 kt sooner, thereby requiring the engine thrust be increased sooner to maintain speed.

A procedure designer can use the results presented earlier to determine the combination of target altitude and the idle-thrust

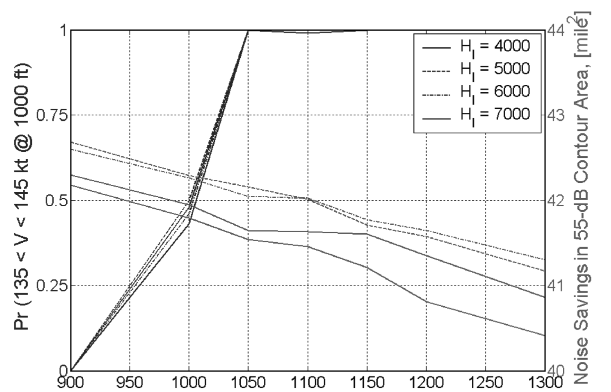

Fig. 11 Tradeoff between the probability aircraft in speed window at 1000 ft and noise savings.

altitude that resolves the tradeoff between the reduction in the noise impact and the probability that the aircraft reaches the required speed window. In this case, to guarantee that the aircraft will be inside the required speed window, the flap schedule needs to be designed for a target altitude of 1050 ft, 50 ft above the required altitude. This 50-ft increase reduces the noise savings in the 55-dB contour area by 0.25 square miles. With a target altitude of 1050 ft, an H_I of 5000 ft provides the highest noise savings.

It was of interest to determine the sensitivity of the noise reduction and the probability that the aircraft is inside the required speed window to increased variance in the pilot delay, as is the case when turbulence is present. To investigate this, a second set of Monte Carlo simulations was conducted using the turbulent pilot-response model (see Fig. 10) with a mean equal to 2.3 s and a standard deviation equal to 4.8 s.

The simulation results are shown in Fig. 12. The results indicate that to guarantee that the aircraft is inside the required speed window, the flap schedule must be designed for a target altitude of 1200 ft. At this altitude, the noise savings in a 55-dB contour area is 41.82, 41.85, 41.89, and 41.18 square miles for H_I equal to 4000, 5000, 6000, and 7000 ft, respectively. In comparison with the previous results (in which the noise savings in a 55-dB contour area at 1050 ft is 41.54, 42.05, 42.16, and 41.64 square miles for H_I equal to 4000, 5000, 6000, and 7000 ft, respectively), the noise savings at the target altitude of 1200 ft in the turbulent case and the noise savings at the target altitude of 1050 ft in the nonturbulent case are essentially the same. This suggests that increasing the variation in pilot delay does not negatively impact the mean of the noise savings. The explanation for this is that increasing the variation in the pilot delay results in two opposite effects on the noise impact. Specifically, it requires that a higher target altitude be designed for the flap schedule, which is a negative effect on the noise impact, because the thrust may be required to be engaged above the required altitude. But it also increases the likelihood that the aircraft achieves its final approach speed below the target altitude, which is a positive effect on the noise impact, because the thrust may be engaged below the required altitude.

Another important comparison to note is that in Fig. 12, the probability is clearly highest with H_I equal to 7000 ft, whereas in the case of no turbulence , the probabilities are approximately the same for all H_I. Because the number of flap changes that must be made for the turbulent and nonturbulent cases are the same, this result indicates that when the variation in pilot delay is small, as in the nonturbulent case, the aircraft has enough time to decelerate to the final approach speed. But as the variation in pilot delay increases, the variation in the points at which the flaps are extended also increase, which in turn requires a larger H_I to provide the aircraft enough time to decelerate to the final approach speed. Hence, it makes sense to see that the probability increases with H_I, as illustrated in Fig. 12.

Given the results in Fig. 12 and the desire to have designed parameters that ensure acceptable performance in the worst case, which is the turbulent case, higher values for H_I are better.

C. Strategic Control Design for Robustness to Wind-Prediction Error

Variability in the wind field around the terminal area is another important factor that affects aircraft performance. To gain insight into the impact that wind variability has on aircraft trajectories and to develop strategies to mitigate adverse impact, the speed envelope of an aircraft (B757 in this case) was examined for three wind scenarios: no wind, headwind, and tailwind.

The speed envelopes for the no-wind, headwind, and tailwind scenarios are shown in Fig. 13. The wind speed in the latter two scenarios is assumed to be 30 kt at 10000 ft, decreasing linearly to 10 kt at the airport measurement station (32 ft above the ground). These wind models are typical in the sense that they illustrate the kind of performance and operational problems likely to be encountered, but they are not intended to be definitive in the sense of fully representing worst cases likely to be encountered (e.g., higher wind speeds or wind shears). As shown in the figure, the primary effect of a headwind is that it increases the aircraft's deceleration, compressing the feasible $V_{\mathrm{TOD}} - H_I$ space and shifting both the MPS and MMS lines to the left. For a given V_{TOD}, a shorter distance and time are required to slow the aircraft down to the final approach speed compared with the case in which there is no wind; a tailwind has the opposite effect. In comparison with the case of no wind and headwind, the tailwind decreases the aircraft's deceleration, hence, the aircraft must start at a higher H_I for a given V_{TOD}. The net effect of the tailwind is that it shifts the envelope to the right. It should also be noted that the V_{TOD} is capped at 220 kt, because flap 5 must be extended at the TOD to slow down the aircraft.

The intersection of all three envelopes is shown in Fig. 13. This area corresponds to the parameter space of H_I and V_{TOD} that provides a feasible flap schedule for the three wind conditions considered. Relative to the envelope of each wind condition, the intersecting area is much smaller, with the maximum values of V_{TOD} and H_I equal to 200 kt and 4000 ft, respectively. These values indicate that it is not possible to choose a V_{TOD} above 200 kt (or an H_I above 4000 ft) that will provide a feasible flap schedule for this aircraft in all three wind scenarios. This limitation is undesirable from an operational point of view, because flying at a slow speed such as 200 kt or below increases flight time and maintaining V_{TOD} from an H_{TOD} that can be as high as 7000 ft to an H_I at 4000 ft increases noise impact.

Two conclusions may be drawn from these results. First, it is critical to have the wind information available, because the size of the feasible $H_I - V_{\mathrm{TOD}}$ space depends strongly on the wind. Second, when the uncertainty is very large or when no wind information is available, conservatism dictates that H_I and V_{TOD} are selected for as wide a range of wind conditions as could be expected. This would result in a lower H_I and a slower V_{TOD}, which in turn would reduce the environmental benefit because the procedure would then closely resemble a conventional procedure.

To mitigate these adverse impacts, it is essential to minimize the wind-prediction error. One approach to reconstruct the wind field in the terminal area is by combining the known wind at the surface, the partially known wind-field information around the terminal, the

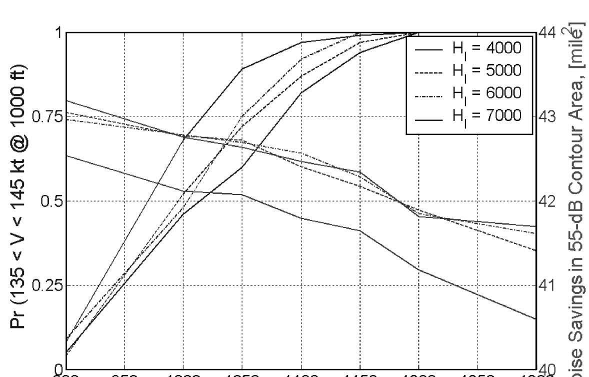

Fig. 12 Tradeoff between the probability aircraft in speed window at 1000 ft and noise savings with turbulent pilot-response model.

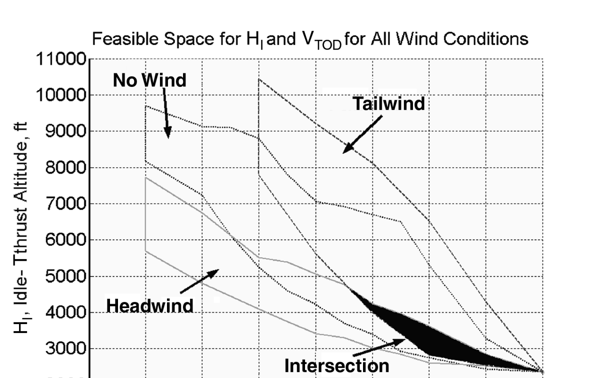

Fig. 13 Speed envelope for all wind conditions.

historical wind data, and the wind information along the flown flight track of each aircraft relayed at a 12-min delayed rate (for security reasons) to a central location on the ground through the aircraft communication addressing and reporting system. Such wind information would provide the bounds on the wind-prediction error and make it possible to implement ANAAPs by choosing appropriate course control variables and developing cueing systems that help pilots make adjustments to the flap schedule. The development of new pilot-cueing systems for this purpose is discussed by Ho [12].

D. Implementation of Strategic and Tactical Control

Air traffic controllers currently issue commands (speed, altitude, course, and clearances) via voice to all pilots under their jurisdiction. This "command and control" operating paradigm will likely continue to be used to manage traffic in the near- to midterm. Thus, the allocation of the strategic control variables between pilots and controllers must be compatible with the way the system currently operates. Although there are many feasible approaches for allocating the tasks, two potential approaches are discussed here to illustrate the range of possible implementations.

The first task-allocation scheme is a distributed control scheme. In this scheme, the controller would determine values for H_{TOD} and V_{TOD}, communicate them and the wind conditions to the pilots via voice, and clear the aircraft to commence its uninterrupted descent at the appointed location. On the airborne side, the pilot would determine H_I, V_F, H_F, the flap schedule based on the wind information provided by the controller, the weight of the aircraft, and the observed or reported turbulence. The pilot would then reduce the thrust at H_I (via dialing the speed down in the speed window in the MCP) and either follow or make the necessary adjustments to the flap schedule to reach the final approach speed at the target altitude. A potential advantage of this task-allocation scheme is that the roles of controllers and pilots are similar to existing standard noise-abatement approach procedures (e.g., the continuous-descent approach being implemented in Europe) and noise-abatement departure procedures. In fact, the mental calculations required of the controller are similar to those required for merging and spacing aircraft in the terminal radar approach control (TRACON). The disadvantage of this task-allocation scheme is that it is challenging for pilots to make adjustments to the flap schedule. Thus, workload is an issue that needs to be analyzed and studied in further detail.

The second task-allocation scheme is a controller-centric control scheme. Under this scheme, all but one of the strategic control parameters are determined by the controller. That is, the controller determines H_{TOD}, V_{TOD}, H_I, and H_F based on the observed winds, the observed or reported turbulence, and the final approach speed provided by the pilot. One potential advantage of this task-allocation scheme is that controllers with the appropriate decision-support tools can determine H_{TOD}, V_{TOD}, H_I, and H_F to very high accuracy, because they have a more global and accurate view than pilots of the traffic and wind along the entire flight path. For example, controllers can obtain and use in their calculations a very accurate and detailed estimate of the wind along the entire flight path by comparing the Aircraft Communication Addressing and Reporting System (ACARS) reported true airspeed and ground speed of multiple aircraft, whereas the pilots might only know the wind at their instantaneous location, the surface wind, and wind information (via ACARS to the aircraft FMC) at four different altitude levels. Another potential advantage is that in the presence of a strong headwind, the controller can maintain the aircraft at V_{TOD} along the descent and delay the time that the thrust is reduced to idle, to mitigate the higher deceleration that comes with a headwind; the opposite would be the case in a tailwind. However, there are some potential disadvantages to the task-allocation scheme. One disadvantage is that in addition to existing tasks, issuing commands for H_I execution will be undesirable, because they would increase the controller's workload, which can be very high in busy terminal areas; consequently, this may be unacceptable with controllers. Another disadvantage is that the pilots' nonconformance or untimely conformance to an H_I command may result in a late initiation of the deceleration, which in turn affects the ability of the aircraft to slow down to the target speed and altitude. The late initiation of the deceleration may be, for instance, a result of the pilots' delay in their response and the delay in pilot–controller communication transactions.

The flap schedule is integral to eliminating undesirable behaviors (e.g., high-thrust transients and significant unplanned level-flight segments) that are caused by pilot delay and/or limitations of the FMS VNAV logic and autothrottle logic [5]. Thus, several cueing systems have been proposed to mitigate the effect of pilot delay and atmospheric uncertainty by providing pilots with cues to help them initiate the procedure and extend the flaps and gear in a timely manner. Three such systems are described here to illustrate the breadth of options that are available.

Researchers at the National Aerospace Laboratory/NLR proposed that a flap cue be displayed in the speed tape of the primary flight display [13]. The cue looks like a speed bug and its position (on the speed tape) provides the speed at which the pilot should extend the flaps and gear. In this approach, the pilot simply executes the procedure by following the cue. If there is a delay in the pilot response, then the onboard algorithm/automation recomputes the new position of the cue. This strategy of exercising closed-loop control on the speed to correct pilot errors ensures that the aircraft meets speed and altitude targets independently of pilot performance for prior targets.

Researchers at the NASA Langley Research Center [14,15] proposed the use of an energy indicator (displayed on the primary flight display) in conjunction with flap/gear-event locations (displayed along the FMS route on the navigation display), driven by their low-noise guidance (LNG) algorithm. LNG calculates a reference vertical trajectory for any lateral route entered into the FMS, based on the aerodynamic performance of the aircraft and predicted/sensed winds. The current version of LNG automatically recalculates the reference trajectory and flap/gear-event locations based on speed, altitude, and route assignments. The energy indicator is continuously updated based on sensed winds and provides fine control over the aircraft's total energy (kinetic and potential energy) as it follows the trajectory. Pilots are expected to maintain the energy within the displayed energy thresholds through the use of the speed brake or throttle, with the autopilot in VNAV PTH, THR HOLD mode. They are expected to select approach flaps and gear upon reaching the event locations shown on the navigation display.

Although the flap speed bugs and energy indicator are viable solutions, they cannot be implemented in the near future, because they require adding new automation capability to or retrofitting airborne equipage. In light of these considerations, researchers at the Massachusetts Institute of Technology [12] proposed that the pilot use a series of gates (or checkpoints), in which the gates are discrete points along the desired speed profile. Each gate consists of an altitude and a speed. The pilot would also be provided with a flap schedule (precomputed before the start of the descent, based on a nominal trajectory) that allows the aircraft to achieve its final approach speed at the required altitude. The gates are developed using Monte Carlo simulation (static solution) or ground-based automation (to incorporate details of current weather). The gates 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 speed from the gate's speed, and based on this deviation, the pilot makes small adjustments to the flap schedule so that the aircraft can meet the next gate and eventually the target. For example, when crossing a gate and the aircraft speed is a few knots faster than desired, the pilot would extend the next flap a bit earlier than suggested; conversely, when the speed is a few knots lower than desired, the pilot would delay extending the next flap. This approach leverages on the pilot's experience and familiarity with the aircraft dynamics to make small adjustments to the flap schedule and hence does not require onboard automation/algorithm. The gate-based cueing system was designed and evaluated in an experiment using a desktop simulator that showed that gates reduce target error to within 5 kt without increasing pilot workload. Interested readers are referred to Ho [12].

IV. Conclusions

The design problem that must be addressed to implement an ANAAP and fully achieve its benefits is that of selecting the procedure parameters that minimize the adverse impact of pilot delay and wind uncertainty. A four-step methodology was introduced to determine the optimum design parameters. In the first step, a simulator-based human-factor experiment was conducted to obtain models of pilot delay in extending flaps/gear in conditions with and without turbulence. The models of pilot delay show that pilots tend to be late in extending the flaps/gear, and to thus mitigate the effect of these delays, the flap schedule must be designed for a target altitude that is higher than the required altitude to ensure that the aircraft will achieve the its final approach speed before the required altitude. However, this results in the engine thrust being increased above the idle-thrust level earlier than desired, to maintain speed, and consequently increases the noise impact. In the second step, the procedure's parameters are formulated as strategic and tactical control variables. This formulation allows the designer to examine the feasible parameter space and how the space changes with the level of wind uncertainty. In the third step, the pilot-delay models and the parameter formulation are used within the context of a Monte Carlo simulation to resolve the conflicting objectives of reducing noise and increasing probability of reaching the required speed window. Simulation results showed that a balance of the objectives can be achieved by having the flap schedule designed to get the aircraft to its final approach speed at a target altitude that is 50 ft higher than the required altitude when there is no turbulence and 200 ft higher than the required altitude when there is turbulence. In the fourth step, the feasibility parameter space is determined for different wind conditions. Results showed that it is critical to have the wind information available, because the size of the feasible parameter space decreases with increased wind uncertainty, substantially undermining the effectiveness of an ANAAP.

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