Design of Aircraft Noise Abatement Approach Procedures for Near-Term Implementation

By

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Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Mechanical Engineering

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ABSTRACT

Advanced aircraft noise abatement approach procedures -- characterized by decelerating, continuous descent approaches using idle thrust, and enabled by flight guidance technologies such as GPS and FMS -- have been shown to reduce operational aircraft noise on communities surrounding airports. However, implementation in the near future presents two challenges. The first is to mitigate the adverse effects on aircraft performance of uncertainties in pilot response, weather, and other system components. The second is to enhance the ability of air traffic controllers to separate aircraft that are decelerating at different rates. The work in this thesis primarily addresses the first challenge by developing, first, a methodology to determine the optimum design parameters for a continuous descent approach, and, second, a new pilot cueing system. The methodology involved: 1) conducting a simulator-based, human factors experiment to obtain models of pilot delay in extending flaps/gear in conditions with and without turbulence; 2) formulating the procedure's parameters as strategic and tactical control variables; 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. Simulation results showed that the flap schedule has to be designed for a 50-ft-higher-than the target altitude without turbulence, and a 200-ft for turbulence; 4) determining the feasibility space of the parameters in different wind conditions. Results showed that when the wind uncertainty is large, accounting for the uncertainty in the procedure design significantly reduces the effectiveness of the procedure. A new pilot cueing system that does not require additional aircraft automation was developed to help pilots manage the deceleration of aircraft and achieve target conditions in a changing environment. The cueing system, consisting of gates (i.e., altitude/speed checkpoints) and a recommended flap schedule, was designed and evaluated in a second experiment using a desktop simulator which showed that gates reduce target error to within five knots and provide comparable performance to that of more automated systems without increasing pilot workload. Because the gates have the potential of enabling aircraft to fly consistent speed profiles, it is hypothesized that their implementation would address the second challenge by enhancing the controller's ability to predict aircraft trajectories and their future separation.

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Acronyms

A/T	Autopilot Auto-throttle
ACARS	Aircraft Communication Addressing and Reporting System
AGL	Above Ground Level
ALT	Autopilot Altitude Hold Mode
ANAAP	Advanced Noise Abatement Approach Procedure
ANOVA	Analysis of Variance
APP	Approach mode
ATC	Air Traffic Control
CAS	Calibrated Airspeed
CDA	Continuous Descent Approach
CDF	Cumulative Distribution Function
DA(H)	Decision Altitude/Height
DME	Distance Measurement Equipment
FAA	The Federal Aviation Administration
FAF	Final Approach Fix
FLCH	Flight Level Change Mode
FM	Feedback Mechanism
FMC	Flight Management System
FMS	Flight Management System
FMS	Flight Mode Annunciator
FPA	Flight Path Angle
FS	Flap schedule
FS-0G	Flap Schedule Without Gates
FS-2G	Flap Schedule With Two Gates
FS-3G	Flap Schedule With Three Gates
GPS	Global Positioning System
HDG	Autopilot Heading Mode
H_I	the altitude at which the thrust is reduced to idle
H_{TOD}	the altitude where the aircraft intercepts the three-degree glide slope
HW	Headwind

ILS	Instrument Landing System
INS	Inertial Navigation Systems
IV	Independent Variable
K	Configuration (flap and gear) schedule
LNAV	Lateral Navigation Mode
LOC	Autopilot Localizer-capture Mode
MFS	Microsoft Flight Simulator
MMS	Minimum Maneuvering Speed
MPS	Maximum Placard Speed
MSL	Mean Sea Level
NFS-0G	No Flap Schedule and No Gates
NW	No Wind
PDF	Probability Distribution Function
PF	Pilot Flying
PM	Pilot Monitoring
RA	Radio Altimeter
RNAV	Area Navigation
SE	Standard Error
SFC	Stabilized and Fully Configured
SI	Autopilot Speed Intervention Mode
SOP	Standard Operating Procedure
TOD	Top of Descent
TW	Tailwind
V/S	Autopilot Vertical Speed Hold Mode
V_F	Target Speed
H_F	Target Altitude
VNAV	Vertical Navigation Mode
VOR	VHF Ominidirectional Range
V_{TOD}	Speed at TOD
W	Wind Vector

Acknowledgement

When I first started this research, I was not sure about my interest in systems engineering in general, or in aircraft noise abatement research in particular, but I was very sure that John-Paul (JP) Clarke would be a fabulous advisor. Not only was I right about the latter, but I also developed a strong interest in noise abatement and systems engineering research, thanks to JP. I was benefited and inspired by his enthusiasm, kindness, caring, pursuit of excellence, and willingness to try out many, actually too many =), of my research ideas. I feel fortunate to have the opportunity to work with and learn from JP as one of his “academic” children =).

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In life we can be beneficiaries or victims of circumstances. I am definitely the former, and my sister and my mom are the latter. While the social and economic conditions in Vietnam did not permit my mom and sister to pursue their academic dreams, I believe that with their formidable aptitude and determination, they, too, could have gotten Ph.D.'s. I would like to dedicate this thesis to them.

1. Introduction

1.1. Motivation

Community concerns about aircraft noise are currently constraining the growth of aviation. Because of the increasingly active legal opposition to airport expansion by residents in impacted communities, many runway expansion projects have either been delayed or abandoned. The net effect is that fewer than five additional runways have been built at the thirty busiest airports in the U.S. within the past ten years [Mead 2000], resulting in greater delays and congestion at major airports [NRC 2001]. Since airports are the nodes of the air transportation system, capacity limitations at the busiest nodes will limit the capacity of the entire system.

A number of measures have been adopted to address the issue of aircraft noise. These measures include: phasing out noisier aircraft [Bond 2001] and introducing aircraft with quieter engine technology [Brookfield et al. 2000]; enforcing nighttime curfews on the operation of all or only certain aircraft; insulating (or purchasing and then demolishing) homes that are severely impacted by aircraft noise [US DOT 1976]; and charging landing fees [BAA 2000]. While these measures have reduced the impact of aircraft noise, they have not reduced the opposition to airport expansion as evidenced by the increase in the number of noise complaints despite the fact that the noise-exposed population remained the same after 1992 (see Figure 1 for Boston Logan International Airport as an example). Given the relatively wide implementation of the measures described above and the potential capacity crisis in the national and international airspace system, there is a critical need for new solutions.

The advent of advanced guidance and navigation systems, in particular multi-sensor Area Navigation (RNAV) systems, including, recently, the Global Positioning System (GPS), offers the opportunity to change aircraft operating procedures in order to further reduce noise. The GPS provides accurate 3-dimensional-position information globally, and RNAV allows aircraft to navigate flexible routes or trajectories created by a series of arbitrary reference points (or waypoints). These capabilities, collectively, may be used to devise thrust management strategies that redistribute noise during departure and arrival, and enable trajectories with noise mitigation as a consideration.

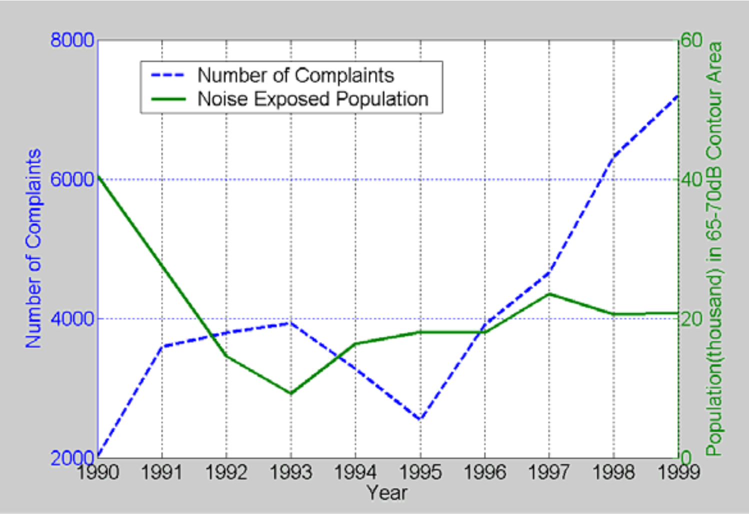

Figure 1: Number of Noise Complaints and Noise Exposed Population in 65-70dB Contour Areas for Boston Logan International Airport. Source: MassPort Noise Office.

As an example, commercial aircraft using the Instrument Landing System (ILS) -- the primary means for commercial aircraft to perform landing -- are required to intercept the glide slope (often three degrees) from below (see Figure 2), 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 the recent trend in airlines is to lower the landing gear early to ensure that final approach configuration is established, the increase in drag due to flap and gear extension requires the engine thrust to be high to maintain the speed. In combination, the maneuvering's close proximity to the ground due to the ILS guidance requirement, the high thrust needed to overcome drag, and the induced airframe noise due to early flap extension at low speeds, produce significant noise impact on those communities along the approach path.

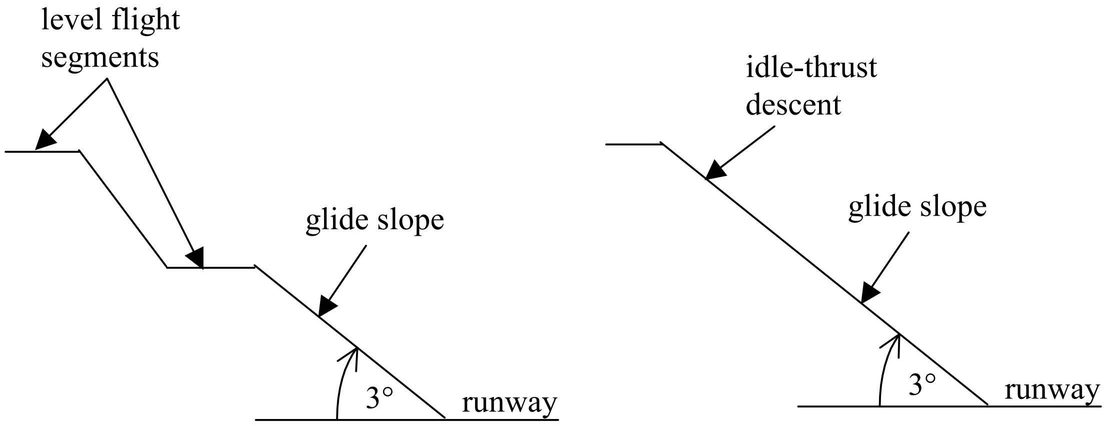

Figure 2: Standard ILS Approach Procedure (left), Advanced Noise Abatement Approach Procedure (right)

With GPS and RNAV, however, virtual descent points can be created to reduce noise impact by allowing aircraft to intercept a virtual glide slope angle at high altitudes and descend along the three-degree approach flight path with thrust set to idle (See Figure 2). Furthermore, the inherent navigational precision provided by GPS and RNAV allows aircraft to closely follow the assigned flight tracks, eliminating dispersions in noise impact that result when aircraft stray from the assigned tracks. Approach procedures that leverage these advanced technologies to reduce noise are referred in this thesis as advanced noise abatement approach procedures (ANAAP). An example of an ANAAP features an aircraft intercepting the glide slope at 7000 feet and descending along the glide slope at idle thrust. The combination of flying at higher altitudes, lower thrust for longer than current standard approach procedures, and delaying flaps and gear extension significantly reduces the noise impact. The noise benefits of ANAAPs have be demonstrated in a number of simulator studies [Clarke 1997; Erkelens 1999; Elmer 2002; Warren et al. 2002] and in a recent field experiment [Clarke et al. 2004], where, both, a reduction of 3 to 6 dB in peak A-weighted noise levels was observed.

While it is equally important to reduce the noise impact of departing aircraft, the focus of this thesis is the development of approach procedures. The rationale for this focus is threefold. First, the development of high-bypass-ratio turbofan engines has significantly reduced engine noise, but the difference in the reduction due to engines is smaller on approach than on departure because, with the way aircraft are currently flown, the engine thrust during arrival is much lower than during departure. Additionally, a large percentage of arrival noise is contributed by airframe noise, which is the aerodynamic noise (excluding engine noise) in the boundary layers surrounding the airplane's body during forward flight.

Second, due to the construction and operation of the navigation guidance systems, the noise impact can be more significant during an approach than a departure. Arriving aircraft have been required to intercept the three-degree glide slope from below and follow the glide slope until touchdown. This requirement results in the aircraft maneuvering for a considerable amount of time at low altitudes (typically at 3000 or 4000 ft above ground level (AGL)), and consequently generating high noise impact. On the other hand, departing aircraft are not subjective to constraints as that of arriving aircraft and are allowed to climb with maximum takeoff thrust. In the past three decades, the improvements in engine performance have enabled departing aircraft to climb quickly, and thus, the energy of the noise attenuates significantly as a result of increasing in distance between the aircraft (the source) and the ground (the receiver).

Third, the technological opportunity for reducing noise during approach is greater than during departure. As demonstrated in [Clarke 1997], advanced guidance and navigation technology allow departing aircraft to adhere to flight tracks accurately and redistribute thrust during climb by selecting altitudes for thrust cutback, as well as the amount of thrust, to distribute noise in a predefined manner. These practices are being used in current operation in procedures such as ICAO Noise Abatement Departure Procedure [Brooks 2002]. In contrast, the progress of the implementation of ANAAPs has not kept pace because of limitations in air traffic control (ATC) capabilities and aircraft performance vulnerability to system uncertainty, as will be discussed in the next section.

1.2. Implementation Challenges

To implement ANAAPs and fully achieve their benefits at airports with high traffic, it is necessary to overcome two significant challenges. One challenge 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 different wind conditions, and on the variable of pilot response time. 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 missed approaches (which result in a go-around and consequently more noise impact).

Another implementation challenge is the inability of air traffic controllers to manually separate aircraft that are decelerating at different rates. The existing strategy controllers use to separate aircraft by commanding aircraft to arrive at common speeds is not applicable to ANAAPs because different aircraft decelerate at different rates. To account for the variability, controllers increase aircraft separation. This practice lowers airport throughput and limits the operation of noise abatement approach procedures to low-traffic environments.

1.3. Overview of the Thesis

The work in this thesis addresses these challenges through the development of noise abatement procedure designs and a pilot cueing system that not only mitigate the effects of system uncertainty on performance but can also be implemented in the near-term. To provide a baseline procedure on which the work is developed, a definition of ANAAPs design parameters and the sources of uncertainties are presented in the first part of Chapter 2. The general guidelines for designing and implementing an ANAAP are presented in the second part of Chapter 2.

In Chapter 3, the design and analysis of ANAAPs is discussed in the context of treating certain parameters as strategic and tactical control variables. With this treatment, sets of feasible flap schedules were first determined based on given values of the strategic control variables, and, then, were used to study the impact of delay in pilot response and wind uncertainty. The pilot delay models used in the study were obtained in a simulator-based, human factors experiment conducted at the NASA Ames CVSRF 747-400 Level-D full motion flight simulator. Then, a numeric Monte Carlo simulation was used to 1) resolve the tradeoff between the uncertainty in pilot response and target achievement; 2) achieve robustness to variability in the wind conditions. A number of concepts for near-term implementation of strategic and tactical control parameters in the current ATC environment are discussed. Because the tactical control parameters implementation involves the use of the vertical navigation mode (VNAV) of the flight management system (FMS), the limitations of existing FMS VNAV logic along with the proposed solutions to overcome these limitations is reviewed. The review shows that the proposed solutions are highly automated and suggests a need for a simple, non-automated pilot cueing system that can be implemented in the near term.

In Chapter 4, a new pilot cueing system is developed. In the cueing system, gates (indicating the expected speed at a series altitude check points) are used to provide pilots information that they can use to adjust the nominal flap schedule, and thus maintain the desired speed profile. Because gates are pre-computed and presented in a paper card, the cueing system does not require additional automation tools, yet, as will be shown, it provides comparable performance in terms of helping pilots manage the deceleration of the aircraft and achieve the target. To gain insights into the development of the gate cueing system for near-term implementation, an experiment is conducted to examine: 1) how and where the gates should be placed; 2) the expected performance with different number of gates with different uncertainty in the wind condition; 3) the pilot's acceptance of the method and strategy to use the gates. The results show that gates, along with a recommended flap schedule, are most useful when placed every 1000 ft along the descent; the absolute value of the speed target error decreases approximately two knots for every additional gate; using gates the subject pilots can achieve the target within a few knots in the presence of wind uncertainty; subject pilots comment that using gates would not increase workload, and that gates are similar to altitude-distance checkpoints in non-precision approach procedures, and to altitude-speed-distance checkpoints in existing continuous descent approach procedures, and, thus, would be easy to use. These results along with the pilots' high acceptance of the gate method suggest that gates have the potential to provide comparable performance to other automated pilot cueing systems, and are worthy of further investigation in real cockpit and traffic environments.

In Chapter 5, two main issues on the integration of ANAAPs into the ATC system are discussed with potential solutions. The first issue centers on the inability of controllers to predict future separation of aircraft performing ANAAPs, and the second issue involves the heterogeneity in the ATC system components. In Chapter 6, a summary of the contributions and conclusions of the thesis is provided.

In the Appendix A, a design principle of using rules/procedures as a means to manage uncertainties and constrain the system behavior into desirable form by providing specific, updated target states toward which the system should be controlled is discussed. In section A.1, the concept is formulated with the design principle that rules can be designed as a mechanism that constrains behavior of a system into a desirable form by providing specific, updated target states toward which the system should be controlled. In sections A.2 and A.3, a generic example (random walk) and an aviation example (VNAV procedure at Eagle, Co) are used to illustrate the concept. In section A.4, the application of the concept to noise abatement approach procedures is demonstrated through the use of procedures to specify the order of thrust-reduction and pitch reduction at the top of descent. In Appendix B, a description of the B737-300/B747-400 simulator is provided. In Appendix C, the data from the experiment in Chapter 4 is presented. A review of considerations other than those discussed in section 2.3 is presented.

2. ANAAPs Definition and Key Drivers for Procedure Design

The definition of ANAAPs design parameters that is presented in the first section below provides a baseline procedure on which the work in the following chapters is based. The rationales for choosing the parameters and the important sources of uncertainty that affect the performance of aircraft flying ANAAPs are discussed in the second section. The general guidelines for designing and implementing an ANAAP are presented in the third section.

2.1. Definition of Procedure Parameters

The profile of a generic ANAAP is shown in Figure 3. The procedure is characterized by the following design parameters:

- W(H): wind vector as a function of altitude H,
- H_{TOD}: the altitude where the aircraft intercepts the three-degree glide slope,
- V_{TOD}: the speed at the top of descent (TOD),
- H_I: the altitude at which the thrust is reduced to idle,
- K[1]: the configuration (flap and gear) schedule,
- V_F and H_F: the target speed and altitude at a specific distance (defined by γ and H_F before landing on the runway occurs, and
- The glide slope angle γ[2], which is nominally 3°.

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[1] 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 are.

[2] This definition assumes the aircraft descends along the glide slope after passing the TOD, but it may be desirable to design the vertical flight path to have several segments with different flight path angles in some cases e.g., using a vertical segment shallower than γ to provide additional drag for a aerodynamically efficient aircraft or to accommodate a strong tailwind.

As shown in Figure 3, 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 descending to the runway, maintaining V_{TOD} until altitude H_I, where the thrust is reduced to idle. From this point onward, the aircraft decelerates to V_F, and if V_F is reached prior to H_F, thrust is engaged to maintain V_F.

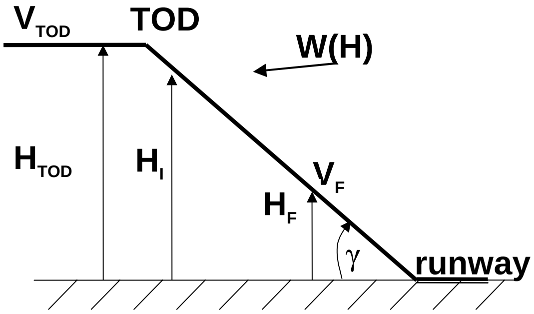

Figure 3: Procedure Definition

On the pilots' side, as shown in Figure 4, because the autopilot and the FMS manage all the aircraft's flight control functions (e.g., idle thrust T_{idle}, and control surfaces such as rudder, aileron, and elevator $U_{rud,ail,el}$) in both the lateral and vertical domains, the pilots' primary task (in addition to other standard tasks such as performing the tasks on their checklists and monitoring traffic or weather or others as stated in the normal final descent procedure) is to determine when to extend the flaps (e.g., speed at which flap is extended U_{flap}) based on their observation of the aircraft's parameters such as the aircraft's position (x), altitude (h), vertical speed (hdot), velocity (v), and deceleration (vdot). The typical pilot procedure for extending the flaps is that on command, via callout of 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.

It should also be noted that while the speed brake can be used to manage the deceleration of the aircraft by increasing the drag, such utility undermines its usage as a compensatory device for contingency situations. Speed brake usage has been considered as a possible solution [ATF 1994] 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 from a human factors point of view because pilots may leave the speed brake extended when not needed. To preclude this, many airlines require the pilot flying (PF) keep a hand on the speed brake whenever it is used in flight [AA 2003]. 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.

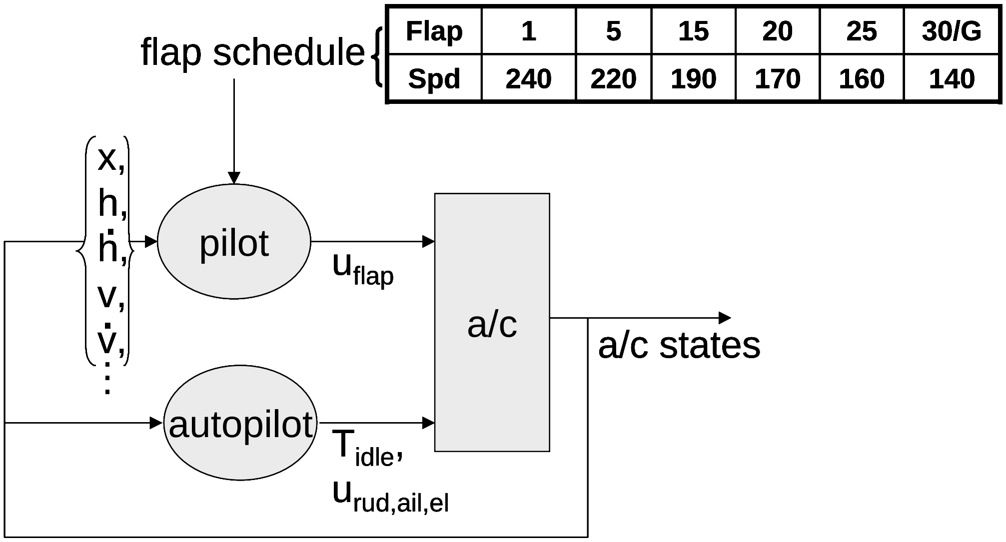

Figure 4: Pilots Control Loop During the Deceleration Segment of ANAAP

2.2. Key drivers for procedure design

2.2.1. Objectives of System Stakeholders

Because ANAAPs are developed to operate in the national airspace system, the design parameters are synthesized to satisfy the goals set by three main stakeholders: the residential community surrounding airports, the pilot, 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 where the aircraft has to fly at low altitudes and low speeds for extended periods, aircraft flying the ANAAP depicted in Figure 3 intercept the glide slope at a high altitude, typically 6000 or 7000 feet, and decelerate along the glide slope from a V_{TOD}, typically at 210 to 250 knots, to the approach speed at idle thrust. Because the average speed in an ANAAP is higher than in a standard ILS approach, the flaps and gear are extended later in an ANAAP than in a standard ILS approach procedure. 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 pilot 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 value of the ANAAPs 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, while 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 glide slope angle can be chosen to match that of the existing facility (typically varies between 2.5 degrees and 3.1 degrees). It is also important to note that although a fixed flight path angle, such as three degrees, 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, one or a combination of these design changes is required: the top of descent must be brought in closer (than in a straight-in approach), a higher value of H_I is used, and a small non-idle thrust is required to maintain the vertical path.

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 Figure 3, 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. Prior to landing, 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[3], forcing the aircraft to break off the approach. The target speed and altitude also ensure that the speed is reduced to a range that allows the aircraft to satisfy the requirement of being fully established and stabilized in the landing configuration by 1000 feet AGL; otherwise a go-around is mandatory. This requirement is critical because a "rushed" approach is the leading cause of approach and landing accidents, including controlled flight into terrain [Cunningham 2003]. For convenience in the analysis throughout this thesis, the target speed and altitude, H_F and V_F, will be assigned to the altitude and speed that satisfy the stabilized and fully configured (SFC) criteria and will be referred to as the SFC target. In practice, commercial airline pilots conventionally aim for a window of plus or minus five knots of the SFC speed and altitude. This convention will be used throughout this thesis.

The parameters V_{TOD}, H_{TOD}, H_I, and the configuration schedule can be integrated into different methods that controllers use to sequence and separate aircraft. The integration highly depends on the communication, navigation, and surveillance capability of current and future ATC environments, and will be discussed in more detail in Chapter 3 and Chapter 4.

2.2.2. Sources of System Uncertainty

To achieve the objectives of all stakeholders, the most critical design challenge remains the management of the effects of system uncertainty on the performance of aircraft flying ANAAP. One of the most important sources of uncertainty is wind prediction error, which stands out as one the largest sources of trajectory prediction error [Williams al et. 1998]. In actual operation, the wind field at the surface is known, but the wind field along the descent path is not completely known. While the magnitude and direction of the wind at the current location can be determined

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[3] The wake turbulence separation requirements aircraft in different weight classes and relative positions in a queue are documented in the Federal Aviation Administration Order 7110.65.

instantaneously by onboard inertial navigation systems (INS), the wind information further along the trajectory is anywhere between zero to six hours old and only available every 3000 feet. The resulting wind prediction error would decrease the effectiveness of ANAAP. For instance, in the idle descent phase 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 requires a non-idle thrust level to maintain V_F, and thereby, increases the noise impact.

Another important source of uncertainty that can significantly reduce the effectiveness of ANAAPs is the variability and latent delay in pilot response. This uncertainty results from the unconventional techniques and operation paradigms of ANAAPs that would not have otherwise been associated with standard approaches. An example is the pilot's usage of flaps and gears. In a standard ILS approach, the flaps and gear are used primarily to transition the aircraft speed from one range to another. Many airlines' operating manuals such as that of American Airlines [AA 2003] 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." 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" [Boeing 2003]. Consistent with these technique guidelines, pilots generally do not use flaps and gear as the primary means of slowing down the aircraft. In contrast, the performance of aircraft flying ANAAPs depend critically on the ability of pilots to extend the flaps and gear at the right moments in order to slow the aircraft to a target while decelerating at idle thrust.

Pilot conforming to ATC commands is another example. In the existing operation paradigm, pilots have the discretion, although within a reasonable limit, of determining the instant when to execute the command. For instance, during an approach, upon receiving an ATC command to descend to a lower altitude and maintain the current speed, the pilot may not initiate the descent immediately because generally the command is not time critical in nature. In contrast, pilots performing an ANAAP need to promptly initiate the descent in order to ensure a stable control flight along the descent path and fully achieve the 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 dissimilar assembly or manufacturing processes.

2.3. Guidelines for Designing an ANAAP for a Specific Airport and Aircraft

In this section, the guidelines for designing an ANAAP are discussed in two levels. The first level, discussed in section 2.3.1, describes the energy equation governing the basic flight mechanics of an aircraft decelerating; and how the equation can be utilized, without extensive simulation or flight test verification, to determine a preliminary set of the procedure's parameters. In the second level, more general recommendations are described in Section 2. The recommendations are for refining the preliminary parameters in a research project by conducting further analysis with simulation tools of different levels of sophistication; and eventually using the result of this analysis to synthesize a baseline procedure for actual flight tests for a specific airport and aircraft.

2.3.1. Preliminary Design Using Energy Equation

To understand the aircraft's flight dynamics during the deceleration, it is instructive to first review the energy equation, which shows the physical forces that cause the deceleration and the aircraft performance characteristics that determine it. For an aircraft decelerating and descending along a vertical flight path, the rate of change in its total energy (i.e., the sum of the potential and kinetic energy) is equal to its velocity times the sum of the forces (i.e., drag and thrust). Assuming that the aircraft is modeled as a point mass, then the energy balance equation for the aircraft is

$$W\,h + \tfrac{1}{2}\,(W/g)\,V_g^2 = \int(T-D)*V_g\,dt, \tag{1}$$

where W is the weight, h is the altitude, g is the gravitational constant, V_g is the ground speed, T is the thrust, D is the drag, and t is time. Taking the time derivative and assuming that W stays constant with time give

$$dh/dt + (V_g/g)*dV_g/dt = (T-D)*V_g/W \tag{2}$$

The assumption of constant W is valid because the fuel burnt during the approach is typically a very small fraction of the total aircraft's weight. Furthermore, assuming that the lift, L, is approximately equal to W, and then the above equation can be rewritten as

$$\sin(\Gamma) + (1/g)*dV_g/dt = (T/W) - C_d/C_l, \tag{3}$$

where Γ is the flight path angle, and C_d and C_l are the drag and lift coefficients, respectively. The effect of winds is captured in the ground velocity, V_g, which is the sum of the indicated airspeed and the speed of the wind. The above equation shows the fundamental relationship of the deceleration, dV_g/dt, as a function of the flight path angle, the ratio of the thrust and weight, and the ratio of the drag and lift coefficients. In order to use the above equation to estimate the parameters of an ANAAP, it is important note that because VNAV can hold a specified flight path angle and the thrust is reduced to near idle or idle when the aircraft is decelerating, the deceleration at each point along the approach can be determined by examining how the ratio of the drag and lift coefficients for each flap setting changes as the aircraft decelerates and using this to compute an average deceleration for each flap setting. Based on this computation, for a given wind condition and an initial condition at the top of descent or any other arbitrary point, different flap schedules can be synthesized to meet the target speed by choosing the range of speed (or time duration or distance) that each flap setting should remained extended.

While the procedure's parameters obtained by using the energy-based method are only preliminary estimates, they are useful in helping the designer understand the tradeoff among the competing objectives.

2.3.2. Procedure Design in a Research Project

Given that estimates of the procedure's parameters had been obtained, the designer's next step is to choose whether to run a simple computer simulation based on aircraft performance characteristics to refine the parameters and explore the effect of winds; run a complex Monte Carlo Simulation taking into account for other factors such as flap extension time (each flap takes some time to mechanically extend to its full extended position), uncertainty in pilot response, and uncertainty in wind predictions; use a level D simulator to determine the FMS parameters; and validate the procedure with a flight test. The general descriptions of these steps are described below.

1. Verify and refine the procedure's parameters with fast-time computer simulation: Create a point-mass dynamic model of the aircraft (see Appendix B for an example) and build a fast-time computer simulation based on the aircraft performance data. Use the simulation to refine the procedure's parameters by obtaining profiles of the aircraft states (e.g., attitudes, speed, thrust, and altitude); exploring the effect of different wind conditions; and ensuring that the procedure meets the basic requirements (e.g., the flap schedule doesn't violate the placard and minimum maneuvering speeds, and the adequate deceleration is provided for achieving the target)
2. Establish the performance tradeoff and initial separation required between aircraft: Conduct fast time simulation, as outlined in section 3.2, to study a) the performance tradeoff between noise reduction and target achievement; b) the feasible operating envelope for the aircraft for certain levels of uncertainty in the wind prediction and pilot response time. Conduct Monte Carlo simulation studies, as discussed in Appendix A.4, to determine the initial required separation between aircraft and to ensure that the aircraft maintain required separation standards throughout the approach.

3. Determine the FMS parameters of the baseline procedure: Establish the speed and altitude constraints for the profile. Over the range of the expected landing weight, simulate the procedure in a level-D certified simulator and reiterate the parameters based on the tradeoff among flight time, noise reduction in specific areas, potential thrust transients or level flight segments, and adequate deceleration for aircraft to slow down. The reader is referred to section 3.4 for FMS and auto-throttle considerations in designing the procedure.
4. Determine a pilot procedure and cueing system: Develop a pilot procedure based on the established FMS parameters and fast time simulation results. The pilot procedure should include adequate details of the decision-making process and steps for executing the procedure. Depending on how the altitude and speed constraints are placed on the profile, incorporating a cueing system (see section 3.4.3 and chapter 4) to prevent thrust transients, excessive or inadequate deceleration.
5. Evaluate the robustness to winds with level-D simulators: Obtain several wind profiles that would be representative of the actual wind conditions and determine the mean and 2-sigma wind profiles. Simulate the procedure in these wind conditions and determine the deviation from the designed procedure. If the deviation is unacceptable, reiterate the procedure design.
6. Flight test: With real aircraft, perform a flight test, collect data, and reevaluate the feasibility of the procedure. Solicit controllers and pilots for their feedback, especially on workload.

For a review of other considerations, the reader is referred to Appendix D.

3. Managing Uncertainty Through Strategic and Tactical Control

The ANAAP parameters defined in Chapter 2 provide a baseline procedure for design and analysis. In this chapter, the design and analysis is discussed in the context of treating certain ANAAP parameters as tactical and strategic control variables[4]. In section 3.1, it is shown that certain parameters produce behavior similar to that of strategic control variables, and thereby, can be treated as strategic control variables in the procedure design. Similarly, the parameters that have "fine-tuning" characteristics are designated as tactical control variables. The utility of strategic control variables to design ANAAPs that are robust to variability in pilot response and wind prediction errors are explored in section 3.2. In section 3.3, two concepts for implementing strategic control variables in the current ATC system are proposed. The concepts center on allocating control authority between controllers and pilots, and, in addition, suggest that the FMS is an enabling factor for the near term implementation of tactical control. A summary of well-known issues in the application of the FMS in the terminal area is presented in the first part of section 3.4. In the second part of section 3.4, some potential solutions that are subjects of current research are presented. While these solutions are viable, they are long-term oriented because they require new automation systems in the cockpit, and thus, provide motivations for the development of new, pilot cueing systems that can be implemented in the near term.

3.1. Tactical and Strategic Control Formulation

The ability of an aircraft to decelerate to achieve the target depends on the aircraft's drag 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, called the Maximum Placard

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[4] As defined in this thesis, in a control system consists of 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 mechanical scale, the strategic control variable is the 50-lb (strategic) graduation, whereas the tactical control variable is the .2 lb (finer) 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 lbs of the actual weight, the bearing on the .2-lb graduation is then adjusted to determine the weight in .2-lb resolution.

Speed, and a lower speed limit, called the Minimum Maneuver Speed. The upper limit prevents structural damage, while the lower prevents stall). Thus, for a given wind condition and a H_{TOD}, the design problem centers on choosing a feasible set of ANAAP parameters (see Figure 3 for reference), consisting of H_I, $V_{TOD,}$ and K, that enable the aircraft to achieve the target. 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 Figure 6:

1. $K = f(V_{TOD}, H_I)$, 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. $V_{TOD} = f(H_I, K)$, where V_{TOD} is determined by fixing H_I and K, which means that for a given choice of H_I and $K_,$ different $V_{TOD's}$ can be designed to achieve the target;
3. $H_I = f(V_{TOD},K)$, where H_I is defined by fixing V_{TOD} and K, which means that for a given choice of V_{TODs} and $K_,$ different $H_{I's}$ can be designed to achieve the target.

While all three relationships may be used in the procedure design, it makes sense to use the first relationship because the parameters V_{TOD} and H_I can only be selected once prior to the point the thrust is reduced to idle, 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 adjusted more than once because it has up to six states (flap settings), and thus, can be used to account for uncertainty in the wind and in pilot response. Moreover, in their radio voice communications to pilots, controllers issue commands with even numbers, typically in multiples of 1000 feet for altitude commands and in multiples of 10 knots for speed commands. In this sense, V_{TOD} and H_I can be treated as strategic control variables and the flap schedule can be treated as a tactical control variable.

Based on these observations, the goal of the design 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, an example using a generic B757 is examined. The envelope for a B757 weighing 180,000 lbs and operating in no wind is shown in Figure 5. The target is 170 knots at 2350 ft. The Maximum Placard Speed (MPS) and Minimum Maneuvering Speed (MMS) for each flap setting are shown in Table 1 below. As shown in Figure 5, the parameter space of H_I and V_{TOD}, where feasible flap schedules exist, is inside the area bounded by the MMS and MPS lines. V_{TOD} is capped at 240 knots because the aircraft must have flap one extended in order to slow down. For every pair of

H_I and V_{TOD} inside this area, except along the MMS and MPS lines, there exists an infinite number of flap schedules since mathematically $K = f(V_{TOD}, H_I)$ and K is not unique for a given pair of V_{TOD} and H_I.

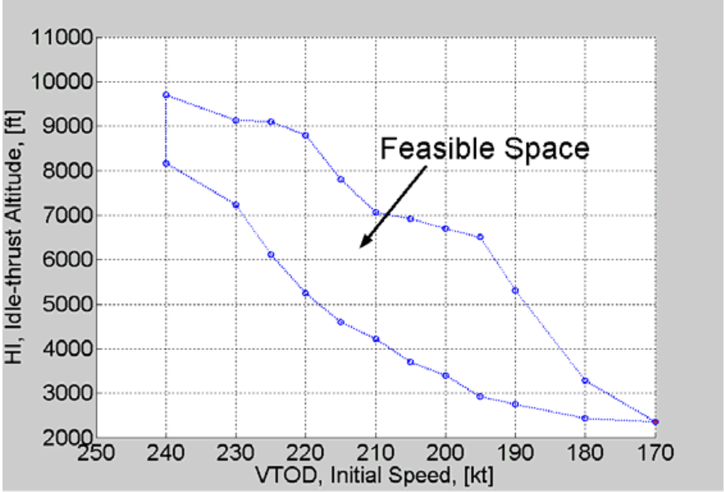

Figure 5: Envelope of H_I and V_{TOD} that Provides Feasible Flap Schedules.

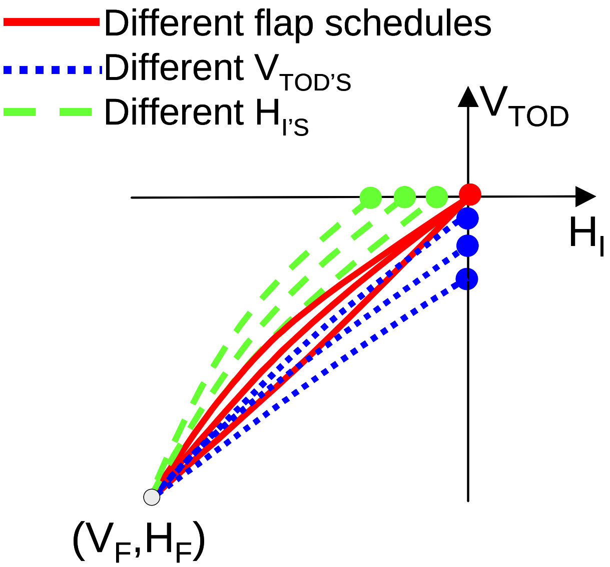

Figure 6: Speed vs. Altitude Profiles for Different Flaps Schedules, Different V_{TOD}'s, and Different $H_{I'S}$

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

Table 1: Minimum Maneuvering and Maximum Placard Speeds

It is also interesting to note in Figure 5 the general trend of increasing V_{TOD} with increasing H_I. This occurs because increasing H_I lengthens the decelerating 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 to decelerate to the target. In other words, if H_I is high and V_{TOD} is small, then the aircraft will decelerate to the target speed prior to reaching the target altitude. Conversely, if H_I is small and V_{TOD} is large then the aircraft will reach the target altitude at a speed higher than the target speed.

Another separate, important consideration in choosing V_{TOD} is the aerodynamic performance of the aircraft. For many aerodynamically efficient aircraft, if the flap is not extended to the first or second position prior to the aircraft commencing the idle descent to the runway, the aircraft may accelerate due to insufficient drag. For instance, the B757 at clean configuration (flap zero) would accelerate at H_I if V_{TOD} were above 210 knots. Therefore, the flap one position must be extended prior to reaching H_I, but this is done at the expense of increasing the airframe noise.

Although treating H_I and VTOD as strategic control parameters allows the pilot make adjustments to the flap schedule to cope with unforeseen changes in the wind or uncertainty in pilot response, the result demonstrated in Figure 5 indicates that the parameter space that the designer of ANAAPs has to work with is much smaller than that of conventional approaches, where the aircraft can be initialized anywhere and still achieve the target speed because pilots have the discretion of using the speed brake or the thrust to slow down or speed up the aircraft as often as needed. This implies that in the presence of uncertainty in the wind or in pilot response, achieving the target requires not only an understanding of how the feasible space changes but also development of cueing systems that help pilots perform tactical control, as it is not viable to task pilots to come up with and make adjustment to a flap schedule. These issues will be addressed in section 3.2.2 and Chapter 4 of the thesis.

3.2. Strategic Control Design for Robustness to Pilot Uncertainty and Wind Prediction Error

3.2.1. Robustness to Pilot Uncertainty

3.2.1.1. Modeling Pilot Response Time

The variability in pilot response affects aircraft performance. The pilot can be early or late in initiating the procedure at the TOD, in reducing the thrust to idle at H_I, and in extending the gear and flaps throughout the descent. As demonstrated in Figure 7, when the pilot is early, the aircraft reaches the target speed prior to the target altitude, the thrust must be increased from idle to maintain speed, and, consequently, the non-idle thrust level increases the noise impact. On the other hand, when the pilot is late, the aircraft reaches the target speed after the target altitude, the aircraft may be too fast to land, or not be in fully stabilized and configured position, which, in either case, may lead to a missed approach. Thus, it is important to understand the impact of the variability in the pilot response has on the aircraft and develop strategies to mitigate adverse impact.

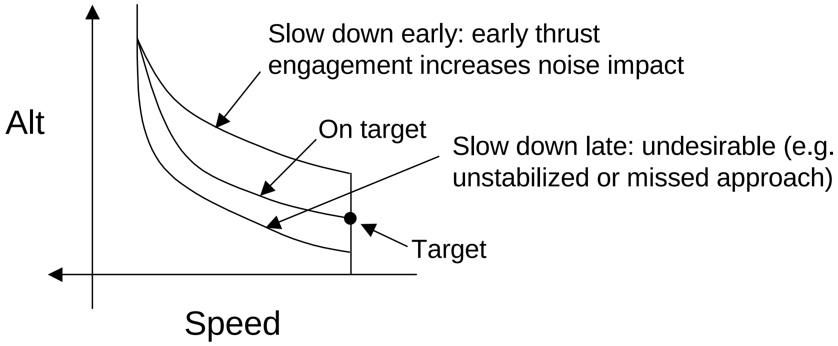

Figure 7: Speed Profiles for Late, On Target, and Early Pilot Response

To investigate and build a model of pilot response time, an experimental study was conducted in the NASA Ames Research Center Crew-Vehicle Simulation Research Facility (CVSRF) B747-400 level-D full motion flight simulator. Complete experimental setup and protocol are reported in [Ho 2001; Elmer 2001]. One of the objectives of this experiment was to measure the pilot response time in initiating the procedure at TOD, reducing thrust to idle, and changing gear and flaps. The eight subjects were airline captains and first officers. They used the autopilot to manage the flight control functions and flew a continuous descent approach (similar to the one in Figure 3) to London Heathrow Airport using a predetermined speed flap-gear schedule. The pilot delay time, defined as the difference of the time when the pilots extended the scheduled flaps minus the scheduled time, was recorded for each run. With this definition, a negative delay time indicates that the pilot is early.

The histogram and the curve-fitted probabilistic distributions (solid lines) of the pilot delay time are shown in Figure 8-Figure 10 for three cases: 1) the pilot flying (PF) provides the cue for the pilot monitoring (PM) to extend the flaps/gear; 2) the PF provides the cue for the PM to extend the flaps/gear with 25% rate of turbulence[5]; 3) the PF extends the flaps/gear himself. Without turbulence, the variance of the pilot response time is smaller when the PF makes the flaps/gear changes without cues from the PM. This makes sense because the PF does not have to cue (via callout) the PM to move the flap and gear handles. The presence of turbulence increases the variance of the pilot response time as expected because the pilots have to cope with the random variations in speed and altitude caused by turbulence.

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[5] 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 = 9.038m/s, yaw = 0 rad/sec, roll = .0027 rad/sec. The method of generating turbulence is proprietary to CAE.

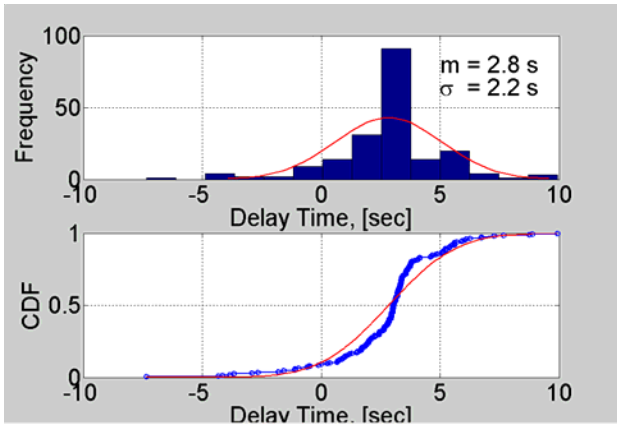

Figure 8: Histogram and Fitted CDF (Cumulative Distribution Function) of Pilot Delay Time (PF Cues PM to Extend Flaps/Gear)

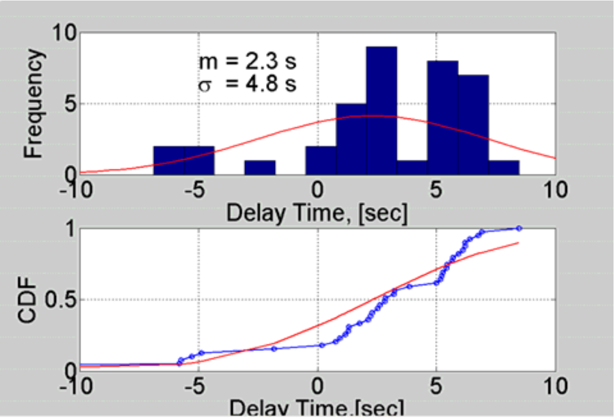

Figure 9: Histogram and Fitted CDF of Pilot Delay Time (PF Cues PM to Extend Flaps/Gear) in 25% Turbulence

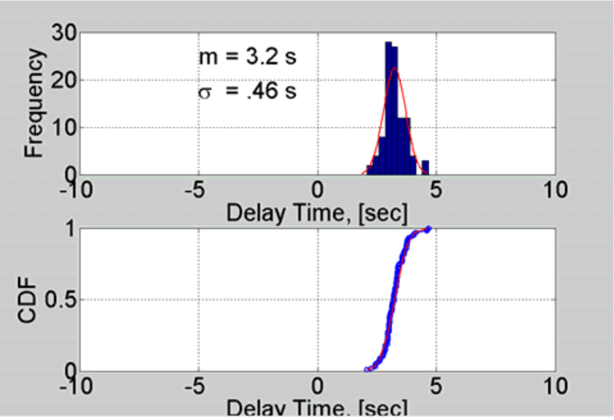

Figure 10: Histogram and Fitted CDF of Pilot Delay Time (PF Extends Flaps/Gear Himself)

Finally, the positive delay time suggests that pilots tend to be on the late side. This delay 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 the procedure, the procedure parameters must be chosen to account for this delay. As shown in Figure 7, the aircraft reaches the target speed (140 knots) at an altitude below the target altitude (1000 ft) when the pilots are late in slowing down the aircraft due to delay in response. (Conversely, the aircraft reaches the target speed above the target altitude when the pilots are early in response.) To mitigate this effect of the delay, the flap schedule must be designed for an altitude higher than the target altitude to ensure that the aircraft will achieve the target. Achieving the target speed (140 knots) prior to the altitude, however, requires the engine to increase the thrust above the idle-thrust level to maintain speed, and consequently, increases the noise impact.

3.2.1.2. Performance Tradeoff: Noise Reduction and Target Achievement

The discussion in the previous section suggests that the objectives of achieving the target (in the presence of delay in pilot response) and reducing the noise impact appear to be in conflict. The design goal is to determine the best combination of the parameters that minimize the noise impact while maximizing the probability that the aircraft meets an assigned target speed window.

To explore this tradeoff, Monte Carlo simulation studies were performed using a high fidelity B737-300 numeric simulation (the simulator is described in Appendix B). In the simulation, the aircraft was initialized to fly at a constant altitude of 7000 feet H_{TOD} at 220 knots V_{TOD}. Upon intercepting the glide slope, the aircraft held its speed at V_{TOD} until reaching a specified $H_{I,}$ and followed a predetermined flap schedule that allows it to reach the target speed at a specific altitude. While there were many feasible flap schedules that would allow the aircraft the reach the target, 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 114000 lbs and the landing flap was set to thirty degrees. Using these values, a Vref of 135 knots and an approach speed of 140 knots (Vref + five knots) were obtained. The SFC target (H_F and V_F) was set to 140 knots and 1000 ft, respectively. The speed window was between 135 knots and 145 knots. The pilot response time was assumed to follow the normal distribution, shown in Figure 8, with a mean of 2.8 seconds and a standard deviation of 2.2 seconds. 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 aircraft's speed is high then they may extend the flap early; if they think that the aircraft's speed is low then 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.

To the tradeoff between noise reduction and target achievement, a set of flap schedules was designed for the aircraft to reach 140 knots at target altitudes ranging from 900 ft to 1300 ft. The idle-thrust altitude was also varied between 4000 ft and 7000 ft, in 1000 foot increments. For each combination of the parameters (target altitude and idle-thrust altitude), the simulation was run (approximately 400 times) until the results converged The probability that the aircraft speed is inside the speed window of 135 knots and 145 knots is shown in Figure 11. As shown in the figure, the aircraft misses the speed window (probability = 0) if the target altitude is below 900 feet, and the aircraft is guaranteed to be in the speed window (probability = 1) if the target altitude is at or above 1050 feet. Furthermore, for a given target altitude, the difference in the probability appears to be small for different values of H_I. This means that this level of uncertainty in the pilot delay doesn't affect the choice of H_I.

The average noise saving in the physical size of the 55-dB contour area[6] in square miles for different values of H_I is shown in Figure 11. The noise saving is defined as the reduction in the noise-impacted area if a noise abatement approach procedure were used instead of a typical ILS

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[6] The 55-dB contour area, a standard aviation noise metric, was computed by using the Integrated Noise Model developed by the FAA (FAA 2005) for evaluating aircraft noise impacts in the vicinity of airports.

approach procedure. The trend in the figure indicates that as the target altitude increases, the average noise-saving decreases. This trend occurs because increasing the target altitude results in the aircraft reaching 140 knots sooner, thereby requiring the engine to increase thrust to maintain speed.

Overall, the results in Figure 11 allow the designer to determine the combination of the target altitude and the idle-thrust altitude that resolves the tradeoff between the reduction in the noise impact and the probability that the aircraft meets an assigned target speed window. In this case, to guarantee that the aircraft will be inside the target speed window, the flap schedule needs to be designed for a target altitude of 1050 feet, fifty feet above the target SFC altitude. This 50-foot increase slightly reduces the noise saving in the 55-dB contour area by .25 square miles. At 1050 feet, H_I equal to 5000 ft provides the highest probability and highest noise saving.

Since these results were obtained using the pilot response model with cues from the PF under non-turbulent conditions, it would be of interest to determine the sensitivity of the noise reduction and probability that the aircraft is inside speed window to the increase in the variance of the pilot delay when turbulence is present. To investigate this, the turbulent pilot response model (see Figure 10) with a mean equal to 2.3 seconds and a standard deviation equal to 4.8 seconds was used to perform Monte Carlo simulation.

The simulation results are shown in Figure 12. The results indicate that to guarantee that the aircraft is inside the speed window, the flap schedule must be designed for a target altitude of 1200 ft. At this altitude, the noise saving in 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 feet, respectively. In comparison with the results shown in Figure 11 (where the noise-saving in 55-dB contour area at 1050 feet is 41.54, 42.05, 42.16, and 41.64 square miles for H_I equal to 4000, 5000, 6000, and 7000 feet, respectively), the noise saving at the target altitude of 1200 ft in the turbulent case and the noise saving at the target altitude of 1050 ft in the non-turbulent case are essentially the same. This suggests that increasing the variation in pilot delay doesn't negatively impact the mean of the noise saving. The explanation for this is that increasing the variation in the pilot delay results in two opposite effects on the noise impact that cancel each other out. Specifically, it requires 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 SFC altitude. But it also increases the likelihood that the aircraft achieves the target speed below the target altitude, which is a positive effect on the noise impact because the thrust may be engaged below the SFC altitude.

Another important comparison to note is that in Figure 12, the probability is clearly highest with H_I equal to 7000 ft, whereas in Figure 11, the probabilities are approximately the same for all H_Is and have largest values for H_I equal to 5000 ft. Because the number of flap changes that must be made for the turbulent and non-turbulent cases are the same, this result indicates that when the variation in pilot delay is small, as in the non-turbulent case, the aircraft has enough time to decelerate to the target. 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 target. Hence, it makes sense to see that the probability increases with H_I as illustrated in Figure 12.

Overall, the results in Figure 12 suggests that if the designed parameters must be designed for the worst case, which is the turbulent case, then choosing high values for H_I provide the best noise saving and target achievement probability.

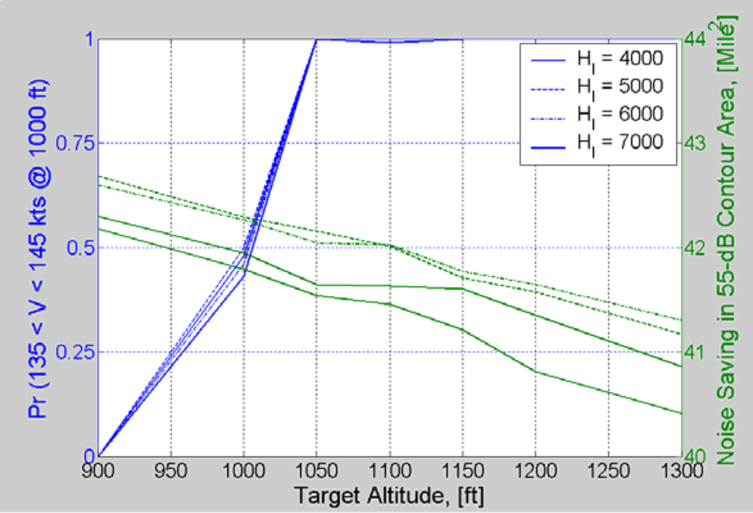

Figure 11: Trade-off between the Probability Aircraft in Speed Window at 1000 ft and Noise Saving

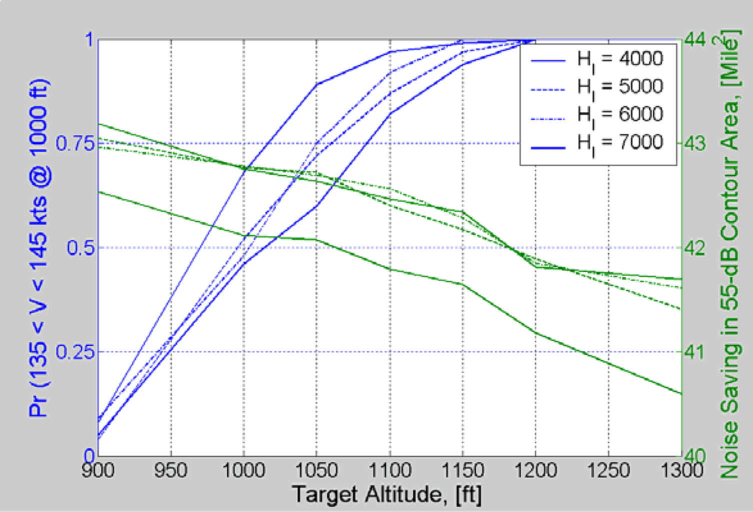

Figure 12: Trade-off between the Probability Aircraft in Speed Window at 1000 ft and Noise Saving with Turbulent Pilot Response Model.

3.2.2. Design for Robustness to Uncertainty in Wind Prediction

The variability in the wind field around the terminal area is another important factor that affects the aircraft performance. To gain insights into the impact of the wind variability has on the aircraft and develop strategies to mitigate adverse impact, the changes in the speed envelope were examined for no wind, headwind, and tailwind.

The speed envelopes for no wind, headwind, and tailwind are shown in Figure 13. The wind is assumed to be thirty knots at 10000 ft and decreases linearly to ten knots at the surface. These chosen 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, compresses the feasible V_{TOD}-H_I space, and shifts both the MPS and MMS lines to the left. For a given V_{TOD}, it takes a shorter distance and time to slow the aircraft down to the target speed compared to the case of no wind. The effect of having a tailwind is the opposite. In comparison with the case of no wind and headwind, the tailwind decreases the aircraft's deceleration and hence requires the aircraft to 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 knots because flap 5 must be extended at the TOD in order to slow down the aircraft.

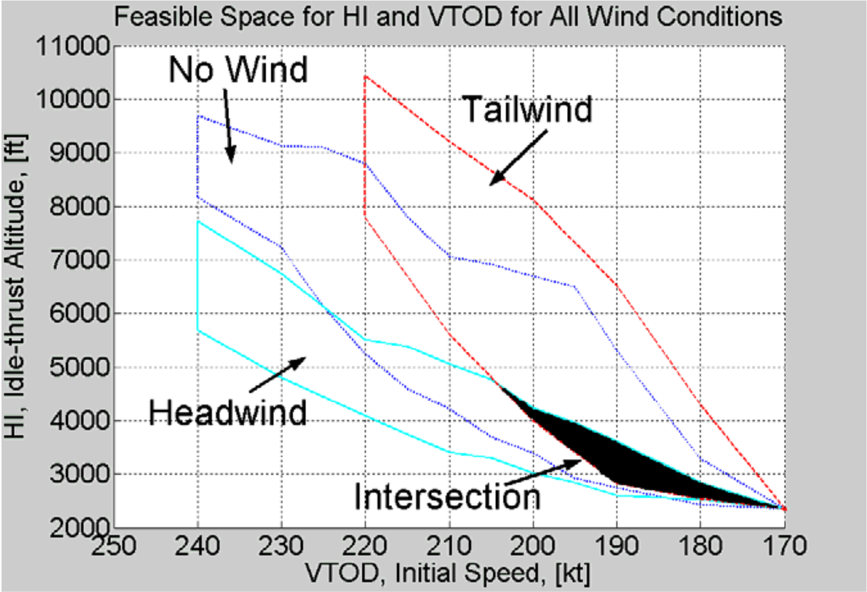

Figure 13:Speed Envelope for All Wind Conditions

The area intersecting all three envelopes is shown in Figure 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 knots and 4000 ft, respectively. These values indicate that it is not possible to choose a V_{TOD} above 200 knots (or an H_I above 4000 ft) that will provide a feasible flap schedule for this aircraft. This limitation is undesirable from an operational point of view because flying at a slow speed, such as 200 knots or below, increases flight time, and maintaining V_{TOD} from a H_{TOD} that can be as high as 7000 ft to a H_I at 4000 ft increases noise impact.

These results have two important implications. First, they suggest it is critical to have the wind information available because the size of the envelope containing the feasible parameter space of H_I and V_{TOD} depends on the level of uncertainty in the wind prediction. Second, when the uncertainty is very large or when no wind information is available, it may not be practical to implement ANAAPs because the limited feasible space would substantially undermine the effectiveness of ANAAP, especially if the speed brake or thrust must be used to compensate for any unforeseen wind prediction errors.

To mitigate these adverse impacts, it is essential to minimize the wind prediction error as much as possible. In existing practice, while the wind at the surface and at the aircraft's instantaneous location are known, the wind field around the terminal area is not completely known because the wind information is anywhere between zero to six hours old and only available every 3000 feet. However, the wind information along the flown flight track of each aircraft is available for relay to a central location on the ground through the Aircraft Communication Addressing and Reporting System (ACARS). Although the wind relayed by the ACARS is delayed twelve minutes for security reasons, it can be combined with historical wind data to either reconstruct the wind field in the terminal area or provide the bounds on the wind prediction error [Ren 2004]. In either case, the knowledge of the bounds on the wind prediction error would make it possible to implement ANAAPs by choosing appropriate course control variables and developing cueing systems that help pilot make adjustments to the flap schedule. The development of new pilot cueing systems for this purpose will be addressed in the following sections and in Chapter 4.

3.3. ATC Implementation of Strategic control

In order to implement ANAAPs in the current ATC environment, two main issues must be considered. The first issue concerns the allocation of control authority between the controller and the pilots. In particular, which parameters should be classified as strategic or tactical control variables, and should the controller or the pilots execute them? The second issue concerns the integration of ANAAPs into the ATC system. The integration centers on providing a means for the controller to maintain the separation between decelerating aircraft performing ANAAP. The second issue will be discussed in Chapter 5. The discussion in this section will be focused on the first issue of control allocation.

In the current ATC operational paradigm, controllers use voice communications to provide ATC commands (speed, altitude, course, clearances) to all pilots currently in the airspace under their jurisdiction. This "command and control" method will continue to be used to manage traffic in the near term. Thus, the allocation of the strategic control variables between pilots and controllers must be compatible with the way the system currently operates. To this end, there are two potential concepts that are worthy of consideration. The first concept involves a distributed control allocation scheme. In this scheme, the controllers would use speed and altitude commands to setup the procedure parameters (H_{TOD}, $V_{TOD,}$ V_F, and H_F), and then clear the aircraft to commence the procedure at a predefined point. On the airborne side, the pilots would perform the procedure by executing tasks such as reducing the thrust at H_I and making adjustments to the flap schedule to reach the target speed and altitude. The potential advantage of this concept is that its operation is similar to that of existing standard approach procedures and noise abatement departure procedures. The disadvantage of this concept is that it is challenging for pilots to make adjustments to the flap schedule to consistently achieve target speed and altitude.

The second concept involves a controller-centric control allocation scheme. Under this scheme, all the strategic control parameters are allocated to the controllers. The potential advantage of this concept is that in addition to having a better overview of the traffic than the pilot, the controller may have a better idea of the wind information along the entire flight path than pilots because the controller can obtain the wind along the entire flight path through the ACARS and by comparing ground speed with airspeed of multiple aircraft, whereas the pilots only know the wind at their instantaneous location and the surface wind. 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. However, there are some potential disadvantages. 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.

While these two concepts have their merits and drawbacks, one of the main deciding factors for choosing one concept over the other lies in the controller's acceptance of the concept. To determine controller acceptance, an interview with sixteen terminal controllers was conducted. These controllers were chosen randomly among the controllers working at the CVSRF facility at NASA Ames and the controllers working at Louisville International Airport in Kentucky. Each controller was verbally given the same description of the two concepts by the interviewer and was asked which concept he would favor and the reasons for his choice. All controllers indicated that they would favor the first concept because 1) it is more compatible with the way the system currently operate; 2) the second concept would increase their workload because they would have to perform "mental gymnastics" to determine where the aircraft should reduce thrust to idle; and 3) the controllers believed that pilots' nonconformance or untimely response would be a serious issue because pilots are too busy during an approach to timely reduce the thrust at a specified H_I.

Given public concern about the impact of aircraft noise and the projected air traffic growth, it is imperative to adopt strategic control concept candidates, such as the distributed control allocation scheme, that have potential for near term implementation of ANAAP. This also implies that it is important to understand the performance of the FMS and its limitations in the use ANAAP, and to develop fine-control implementation concepts that complement these limitations.

3.4. FMS Considerations for Tactical Control Implementation

Because the implementation of the procedure's tactical control parameter, i.e., the flap schedule, involves the use the FMS and the auto-throttle to manage the speed and the vertical profile of the idle-thrust deceleration segment, the basic operational concept of FMS VNAV and auto-throttle during the approach phase are provided in section 3.4.1. This is followed by a discussion in section 3.4.2, which highlights the limitation of FMS/auto-throttle logic through a summary of some well-know VNAV issues, and through a flight demonstration test of a noise abatement approach procedure in Louisville International Airport. In section 3.4.3, a review of proposed solutions to mitigate these limitations is given, and the need for a new solution that can be implemented in the near term is presented.

3.4.1. FMS and Auto-throttle Logic

The FMS was conceived and implemented in early eighties and achieved its operational status in the mid eighties. Originally designed to help minimize the workload in the cockpit during the cruise phase of a flight, the FMS is widely used today in all flight phases, including the approach where the FMS has been an enabling factor for the implementation of ANAAP. In this section, the use of the FMS VNAV for noise abatement is discussed. For a detailed discussion of the FMS and its history, the reader is referred to [Spradlin 1983].

The basic operation concept of FMS VNAV is illustrated in Figure 14. As illustrated, given a set of waypoints with altitude and speed constraints, and an assumed wind and aircraft characteristics, VNAV builds the descent profile backward, starting from the end of the descent (last waypoint) up to the cruise altitude [Bulfer et al. 1996]. The descent profile generally consists of four types of vertical segments: a unique idle segment between the TOD and first altitude constraint; V-PATH straight-descent-line segments between the consequent altitude constraints; sloped 500 foot-per-minute deceleration segments; and level deceleration segments. The 500 foot-per-minute deceleration segments are inserted before waypoints with different speed constraints in descent. Depending on winds aloft, segment steepness, and constraints at waypoints, the FMS executes these segments using three auto-throttle modes: the auto-throttle may reduce thrust to idle (IDLE mode), hold a specific thrust level (THR HOLD mode), or add thrust (SPD mode).

In the idle-thrust segment between the TOD and the first altitude constraint, VNAV computes the TOD and makes adjustments to maintain the vertical path according to winds aloft. For instance, a higher than forecast headwind will result in throttle up to maintain speed, and a higher than forecast tailwind will result in aircraft diving for the path. In the V-PATH segments between subsequent altitude constraints, the thrust may be idle or non-idle, depending on the steepness of the path. For instance, a steep slope will result in an idle-thrust descent, possibly faster than intended, whereas, a shallow slope will result in throttle up to maintain speed.

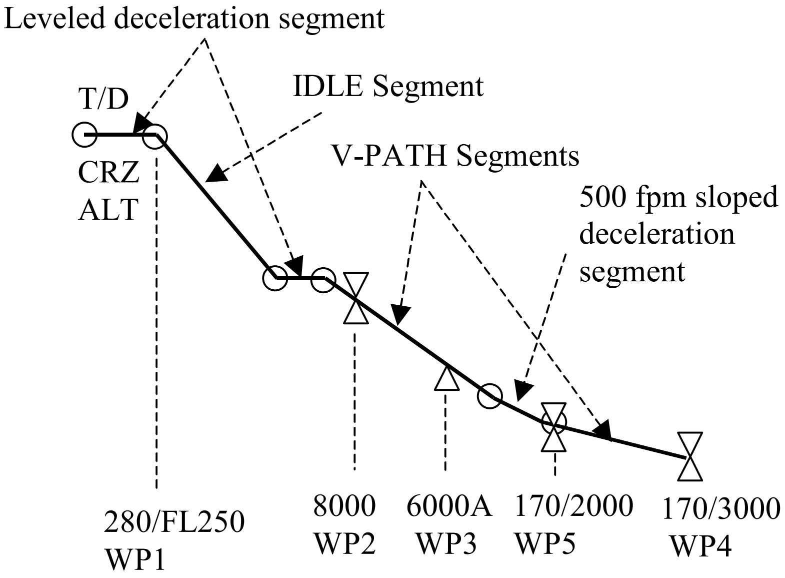

Figure 14: An Example of a Vertical Profile

3.4.2. Limitations of FMS VNAV and Auto-throttle

3.4.2.1. VNAV Well-known Issues

In practice, the VNAV function of the FMS is often used in descent but is rarely used on approach. In a survey conducted by [McCrobie et al. 1997], only five percent of major US airlines pilots reported using VNAV functions in approach. There are many factors account for this infrequent utilization of VNAV. One important factor is the mismatch between tactical ATC operation and strategic FMS flight planning. Pilots often have difficulty entering ATC instructions into the FMS because the task increases head-down time [Lee et al. 1997] and the workload during approach is high.

The low level use of VNAV was also reported in a survey by BASI [BASI 1999]. It was found that sixty one percent of surveyed pilots stated that VNAV produces unintuitive and unexpected behavior. For example, in order to automatically select altitude and speed targets according to pilot MCP entries and constraints in the flight plan, VNAV chooses intermediate altitude targets from a list of 16 and speed targets from a list of 24. The intermediate targets are often not self-explanatory, and the size of these lists is much larger than the small list of targets that pilots are familiar with [Sherry et al. 1999]. The VNAV function of automatically selecting pitch and thrust control modes to fly the aircraft to the targets also often takes pilots by surprise because the autonomous transition between modes are made without pilot actions and often are based on circumstances [Palmer 1995; Javaux 1998]. Another example is the VNAV function of building an optimum path for descent and approach. This function does not provide pilots with intuition of how the path is constructed and information such as the distance to the next waypoint where the deceleration would take place. Some other reported surprises [McCrobie 1997] include deceleration too early, unpredictable speed during descent and approach, and failure to make altitude restrictions.

Operation issues with VNAV were also investigated with cognitive engineering analysis [Sherry 2000]. It was identified that pilots often do not know which mode VNAV is in because selecting the VNAV button results in VNAV using a trajectory from a list of many possible trajectories and changing the commanded trajectory automatically according to the circumstances. As an example shown in Figure 15 from [Sherry 2000], when the VNAV button is selected in the descent phase of a flight plan with the goal of descending to the final approach fix (FAF) from a cruise altitude, the VNAV function commands a set of six behaviors:

1. Descend on FMS Optimum Path
2. Descend Return to Optimum Path from Long (Late)
3. Descend Converge on Optimum Path from Short (Early)
4. Maintain VNAV Altitude
5. Descend Open to VNAV Altitude to Protect Speed
6. Descend to VNAV Altitude, Hold to Manual Termination

As shown in Figure 15, while VNAV attempts to fly the fuel/time optimal path and meet the altitude and speed constraints in the flight plan, errors -- in wind prediction such as a higher than predicted tailwind or in complying with an ATC instructions such as a late descend to a cleared altitude -- will cause the aircraft to be off the optimum path. In response to this, VNAV will switch to Descend Return to Optimum Path (from Long) behavior, which automatically commands a trajectory to bring the aircraft back to the optimum path. Depending on the type of FMS software and logic, VNAV may reduce the thrust to idle, allow an increase in the speed to ensure path convergence, or annunciate an “add drag” or “drag required” message on the Navigation Display.

Currently, research is being conducted to modify the FMS VNAV user-interface to mitigate these problems. Some of the proposals [Sherry 2001] to eliminate the overloading of the VNAV button include: decoupling the FMS flight plan as the source of targets (speed, altitude, vertical speed) from the FMS flight plan as the source of control modes (pitch/thrust) by adding to the MCP a separate input device (called the DES PATH button) to arm the capture and tracking of the path; dynamically labeling what VNAV will do when it is selected by annunciating specific VNAV behaviors; explicitly annunciating on the FMA VNAV control modes (such as DES PATH control mode) that are not conventional Autopilot modes; and annunciating on the FMA VNAV commanded behavior.

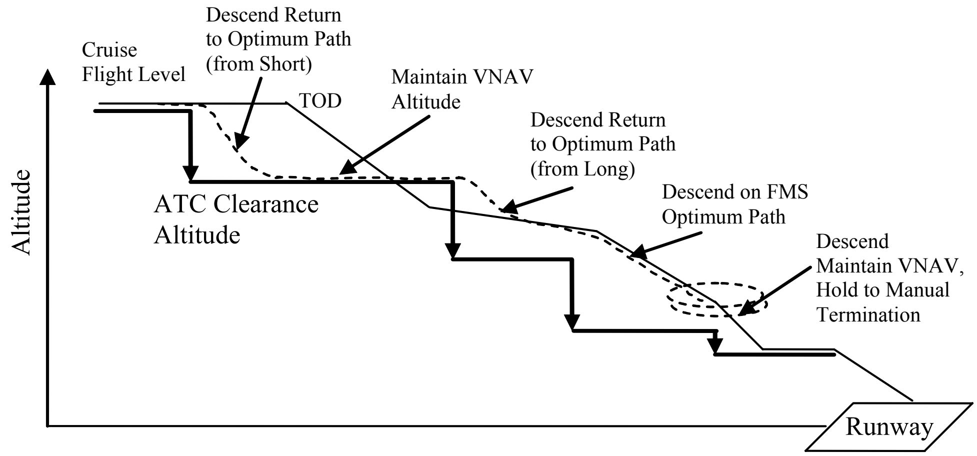

Figure 15: VNAV Behaviors to Descend to the Final Approach Fix (adapted from Sherry, 2000).

3.4.2.2. VNAV Issues in ANAAPs Implementation: Louisville Flight Test

In an effort to further the development of noise abatement procedures, a research team, led by the Massachusetts Institute of Technology (MIT) with members from the Boeing Company, the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), the Regional Airport Authority (RAA) of Louisville and Jefferson County and United Parcel Service (UPS), conducted a flight demonstration test at KSDF to evaluate the operational characteristics and demonstrate the noise-reducing potential of a Continuous Descent Approach (CDA) procedure. In the procedure, B767-300 aircraft descend and decelerate continuously without reverting to level flight to runway 17R at Louisville International Airport (KSDF). For a detailed discussion of the procedure design and the flight demonstration test, reader is referred to [Clarke et al. 2004]. The focus of this section is on how existing FMS VNAV and auto-throttle logic can negatively impact performance.

The ground track defined by waypoints CHERI, BOBBE, JIMME, WOODI, BLGRS, CHRCL and 17R is shown in Figure 16. The altitude and speed profiles are shown in Figure 17, where altitude values are shown on the left vertical axis and Calibrated Airspeed (CAS) values are shown on the right vertical axis. The constant speed of approximately 180 knots near WOODI and BLGRS is intended to avoid thrust transients over the noise-sensitive area. The points at which flap transitions are projected to occur are indicated on the CAS profile.

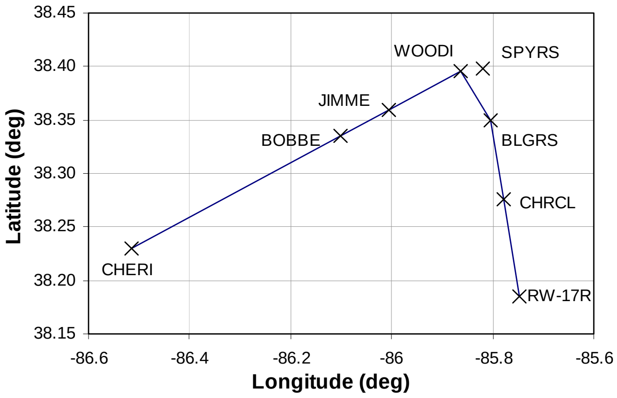

Figure 16: Waypoint Locations for Flight Track

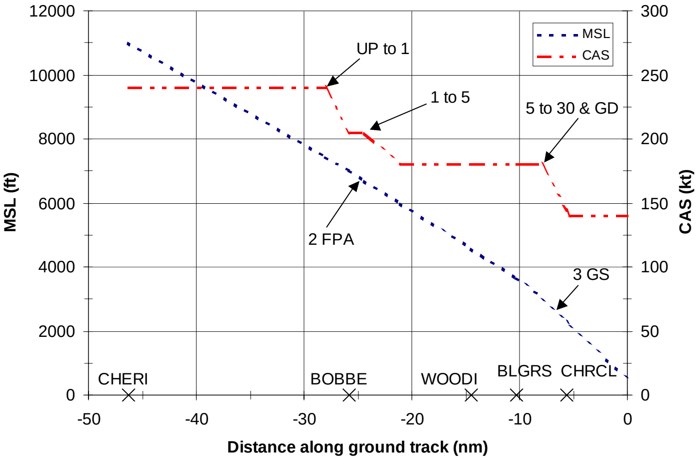

Figure 17: Baseline Procedure Used in the Demonstration Test

Waypoint	Speed Constraint	Altitude Constraint
CHERI	At 240 Knots	At 11,000 ft
BOBBE	No Constraint	No Constraint
JIMME	At 180 Knots	At or Above 5000 ft
WOODI	No Constraint	No Constraint
BLGRS	At 180 Knots	At or Above 3000 ft
CHRCL	No Constraint	At 2350 ft

Table 2: Speed and Altitude Constraints

As an illustration, the flight data on one test day is shown in Figure 18-Figure 20. As can be seen in Figure 18, the aircraft performing the CDA had four distinct thrust transients (significant but short duration increases in thrust) and a level flight segment between JIMME and WOODI. To understand how and why these occurred, the altitude, speed and configuration profiles were examined chronologically to determine how the VNAV and auto-throttle managed the control functions of the aircraft to satisfy the speed and altitude constraints of the CDA procedure.

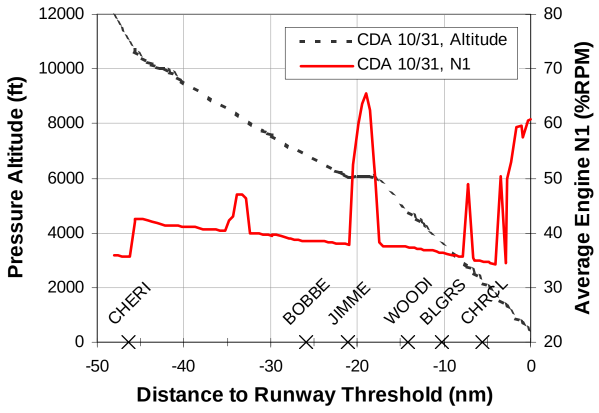

Figure 18: CDA Altitude and Average Engine N1 vs. Distance to Runway Threshold

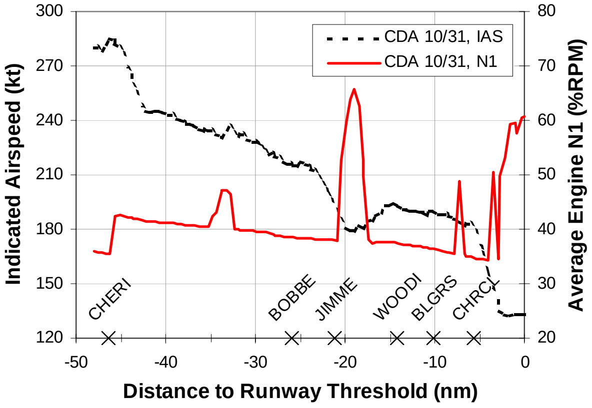

Figure 19: CDA IAS and Average Engine N1 vs. Distance to Runway Threshold

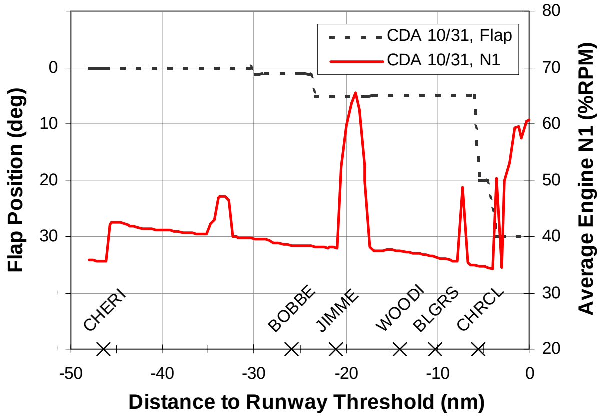

Figure 20: CDA Average Engine N1 and Flap vs. Distance to Runway Threshold

As shown in Figure 18, the aircraft descended from its cruise altitude (not shown in the Figure) to the first altitude constraint at CHERI (11,000 ft) at idle power. While VNAV typically computes an idle descent path from the cruise altitude to the first waypoint with an altitude constraint, the relatively high descent rate may have been the result of an unaccounted for tailwind, the aircraft being handed over from the Center to the TRACON at a higher than normal altitude, or the pilot being late in initiating the procedure. Whatever the cause, the aircraft met the altitude constraint at CHERI, but the speed constraint of 240 knots was reached sometime after the aircraft had passed CHERI (See Figure 19). This result was not surprising given the fact that in the existing VNAV logic the altitude constraint is always given preference over the speed constraint [Bulfer et al. 1996]. That is, when both constraints cannot be met, VNAV will sacrifice the speed constraint in order to meet the altitude constraint provided that speed limitations such as the maximum allowable speed or stall speed are not violated.

Upon reaching CHERI, VNAV slowed the rate of descent to reduce the speed to 240 knots and increased the thrust to a thrust level (which was noticeably higher than idle thrust but still relatively low overall) that it believed would enable a steady deceleration to the speed and altitude constraints at BOBBE (205 knots, 7000 ft). However, as can be seen in Figure 19, a thrust transient occurred when the aircraft reached 230 knots. One likely explanation for this transient is that the auto-throttle, predicting that the aircraft would decelerate below the minimum maneuver speed for the clean configuration and knowing that the flap had not yet been extended to flap 1, increased the thrust to prevent the aircraft from decelerating further. This hypothesis is consistent with the fact that: (a) the aircraft was 10 knots below the maximum allowable speed in the flap 1 configuration; (b) the maneuver speed in the clean configuration for the 767-300 at the recorded weight of 253,000 lbs is 210 knots [AA 2003]; and (c) no thrust transient occurred when the speed returned to 230 knots for a second time (after the flap had been extended to the flap 5 configuration).

Unfortunately, the auto-throttle provided too much thrust, resulting in an increase in the speed of the aircraft. In response to this increase in speed, VNAV slowed the rate of descent to arrest the acceleration and to provide sufficient time to compute the thrust and flight path angle required to make a steady deceleration to the speed and altitude target at BOBBE. As was the case prior to CHERI, VNAV gave preference to the altitude constraint and thus the aircraft was at a higher than appropriate speed when it passed above BOBBE.

Upon reaching BOBBE, VNAV then computed the thrust and flight path angle to meet the speed constraints at JIMME and BLGRS and the altitude constraint at CHRCL. It should be noted that the altitude constraints at JIMME and BLRGS (the aircraft only had to be at or above specified altitudes) were ”at-or-above” constraints so there were many possible flight paths that crossed these locations above the altitudes that were specified. As a result, VNAV was free to choose a flight path to satisfy the speed constraint at JIMME. As shown in Figure 19, the aircraft did indeed meet the speed constraint of 180 knots at JIMME at which point the auto-throttle responded by increasing the thrust to prevent the speed from decreasing any further. As was seen above, the thrust supplied was disproportionate to the increase in drag because the aircraft actually started to accelerate. The response of VNAV, as shown in Figure 18, was to slow the rate of descent, resulting in the level flight segment. This level flight segment arrested the acceleration but during that time the aircraft had flown sufficiently far that it was not possible to decelerate to meet the speed constraint of 180 knots at BLGRS. In fact, the speed at BLGRS was approximately 190 knots, implying that the VNAV failed to meet the speed constraint by 10 knots.

Also shown in Figure 19 is that a third, brief thrust transient occurred just prior to the aircraft reaching BLGRS and 180 knots for the second time. There are two likely explanations for this thrust transient. First, the thrust transient was needed to maintain the speed at 180 knots until the aircraft reached CHRCL. Second, as was the case for the first thrust transient, the auto-throttle commanded an increase in thrust to prevent the speed from dropping below the flap 5 minimum maneuver speed of 170 knots [AA 2003].

The fourth thrust transient occurred during the transition from flap 20 to 30. It appears that the auto-throttle increased the thrust in anticipation that the aircraft would be at its final approach speed when the flap extension was completed but then had to reduce the thrust to enable further deceleration once it became clear that the aircraft was 20 knots above the desired speed.

These results illustrate how pilot delay, FMS VNAV logic, and auto-throttle logic, individually or collectively, produce undesirable behavior. First, when the pilot is late in initiating the procedure, the aircraft will descend to meet the altitude constraint at the first waypoint and then slow its rate of descent after it has passed the waypoint to decelerate to the desired speed. The reason for this is that VNAV gives preference to the altitude constraint over the speed constraint when both constraints cannot be satisfied. Thus, instead of achieving the desired constant flight path angle descent, the aircraft will actually perform a staged descent albeit with very short (near level flight) segments.

Second, when the pilot is late in extending the flap or the aircraft reaches a speed target, the auto-throttle provides more thrust than is required to simply prevent the aircraft from decelerating further. This results from the difficulty in controlling a system (such as the turbo-fan engine) with significant inertia and time lags during spool up and spool down. Thus, the aircraft will begin to accelerate.

Third, VNAV responds to excessive thrust transients by slowing the rate of descent to arrest the resulting acceleration. If the thrust transient is very large (as was the case during the CDA described in the previous section) VNAV will create a level flight segment. Once this maneuver occurs, the aircraft will then be above the desired flight path. In cases where there are both speed and altitude constraints at the next waypoint, the aircraft then has to descend rapidly to meet the altitude target, thus increasing the speed and requiring an additional shallower flight segment to arrest the acceleration. If the subsequent waypoint also has speed and altitude constraints, the sequence of events is repeated (albeit without thrust transients and therefore at lower amplitude).

3.4.3. Potential Solutions

The discussion in sections 3.4.2 highlights a broad range of VNAV issues in general as well as the design considerations for noise abatement approach procedure in particular. These issues explain the low level of use of VNAV in the terminal area and the limitations of the FMS logic. Solutions addressing these issues can be developed either within the context of these limitations if they are to be implemented in the near term, or outside the context of these limitations if they are to be implemented in the long term. The discussion also suggests that efforts should be made, individually and collectively, to (1) reduce pilot delay; (2) create CDA procedures that are robust to pilot delay; and (3) modify the logic of FMS VNAV, the auto-throttle, and Mode Control Panel modes such as the FPA mode so that their responses are in line with the overall objective.

One possible solution 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. Determining the appropriate cues and automation is a topic of on-going research. Researchers at National Aerospace Laboratory in the Netherlands have proposed that a flap/gear cue be displayed in the speed tape of the flight director [Koeslag 1999]. 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 re-computes 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 independent of pilot performance for prior targets.

Researchers at NASA Langley have proposed the use of an energy indicator in conjunction with a flap/gear annunciation (calculated prior to the start of the descent) to help pilots determine when to extend the flap. The energy indicator is displayed in the flight director between the low-energy bar and the high-energy bar. The annunciation is represented by characters such as “FL 1” (for flap 1) or “G/D” (for gear down) or “TOD” (for top of descent) and is displayed on the top of the trajectory in the Navigation/Map Display. In this approach, the pilot executes the procedure by initiating the procedure or extending the flaps and gear as suggested by the annunciations. In addition, the pilot uses the energy indicator to make decisions such as extending the speed brake when the energy is too high or delaying a flap extension when the energy is too low. The energy indicator can also work in a closed-loop fashion if the onboard automation/algorithm re-computes and updates the flap and gear annunciations along the descent.

While the flap speed bugs and energy indicator are viable solutions, they cannot be implemented in the near term because they require adding new automation capability to or retrofitting airborne equipage. The certification process for adding new automation takes a very long time. Furthermore, unless aircraft manufacturers or airlines can find a business case, the automation upgrade may prove to be financially burdensome.

In light of these considerations, there is an imperative to develop solutions that can be implemented in the near term while providing comparable performance to long-term, automated solutions. In the next chapter, a new approach to provide pilot cues for managing the aircraft deceleration is presented.

4. Design and Evaluation of Gates as a Tactical Control Feedback Mechanism

In this chapter, a new pilot cueing system is introduced based on the design principle discussed in Appendix A. The cueing system, consisting of a series of gates (indicating the expected speed[7] at a series of altitude check points), gives the pilots information that they can then use to adjust the nominal flap schedule, and thus maintain the desired speed profile, in response to changing operating conditions. To investigate the benefits of gates as well as their implementation issues, a human factors experiment was conducted. The insights gained from experiment and the implication for the near term implementation of gates are also discussed.

4.1. Gates as a Feedback Mechanism

In the existing practice, pilots fly aircraft according to the commands issued by air traffic controllers[8]. Because the commands are discretized and the transients in the aircraft state in going from its current state to the commanded state are not too important to the controllers, the aircraft's speed, altitude, and heading profiles are essentially made of a series of step-downs. In flying these step-downs, pilots have some flexibility, upon receiving a command, in deciding when to initiate the transition to the commanded state and to take appropriate control actions (thrust adjustment, pitch, roll, yaw) to maintain the commanded state that the aircraft has reached. For instance, during approach, upon receiving a command, "Descend and maintain 7000 ft. Reduce speed to 220 knots", the pilot would first use pitching control actions to descend the aircraft to 7000 ft and adjust the pitch to stay at this altitude. Then, the pilot would adjust the thrust or use the speed brake to maintain the aircraft's speed at 220 knots. Since the pilot is given enough time to make the control adjustments, the pilot could reach and maintain the commands precisely without much difficulty.

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[7] All speeds are airspeed, unless indicated otherwise.

[8] The pilot in command is still directly responsible for, and is the final authority as to the safe operation of the aircraft [FAR 1998].

However, it is very challenging for the pilot to determine, for a given set of strategic control parameters/commands issued by controllers or defined by a procedure, a flap schedule (or the tactical control parameter) to meet the target speed and altitude while the aircraft is decelerating continuously. The challenge lies in the growth in the uncertainty in the aircraft trajectory, specifically the speed profile, and is contributed to by 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 his approximated deceleration may be inaccurate because the wind further 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.

Along with the factors discussed in section 3.4.3, this discussion suggests that the design principle, developed in Appendix A, can be utilized to develop a new cueing system that: 1) helps the pilot mange the growth in uncertainty in the aircraft's speed profile by resetting the system states; 2) mitigate the effect of pilot delay and wind uncertainty; and 3) can be implemented in the near term and provide comparable performance to that of more automated solutions. To meet these objectives, a concept of using a series of gates or checks, which are discrete points along the nominal speed profile, is proposed, investigated, and evaluated. As defined in this thesis, each gate[9] consists of an altitude and a speed (unless noted, all speeds are indicated airspeeds). The pilot would also be provided with a flap schedule that allows the aircraft to achieve the target. Both the flap schedule and the gates are pre-determined based on the nominal trajectory, nominal wind condition, and the dynamics of the aircraft. The gates are used in conjunction with the 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 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 (see Figure 21). 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

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[9] This definition is different than the definition in the FAA Order 7110.65, which defines the gate as the approach gate a mile outside the final approach fix used by the controller.

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 essentially reinitializes the state of the system since the pilot's future decision is based solely on the current observed speed deviation. The initialization also enables the pilot to determine the adjustment to the flap schedule. The adjustment to meet to target resets the growth in uncertainty of the speed. Because the gates and the flap schedule can be computed offline, they have the potential to be implemented without adding any onboard automation.

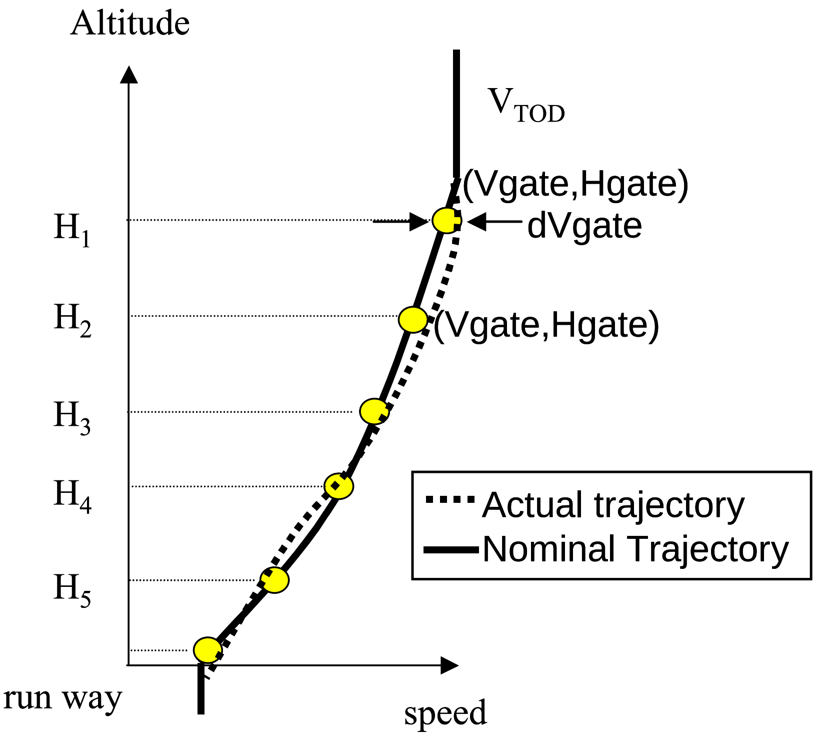


Figure 21: Gates as a Feedback Mechanism

It is also important to note that the concept of using "gates" as a feedback mechanism to reset the growth in the uncertainty and reinitialize the system states is similar to a number of other concepts used in the existing noise abatement approach procedures and non-precision approach procedures. For example, Alitalia Airlines fly the CDA in Europe by using a special chart (see Figure 22) that recommends pilots achieve certain speed/distance and configuration at specific altitudes along the final approach segment. In this context, each recommended speed/configuration at an altitude provides feedback to the pilots to make corrections when the aircraft deviates from the desired trajectory, and thereby, enable the aircraft to descend continuously without reverting to level flight.

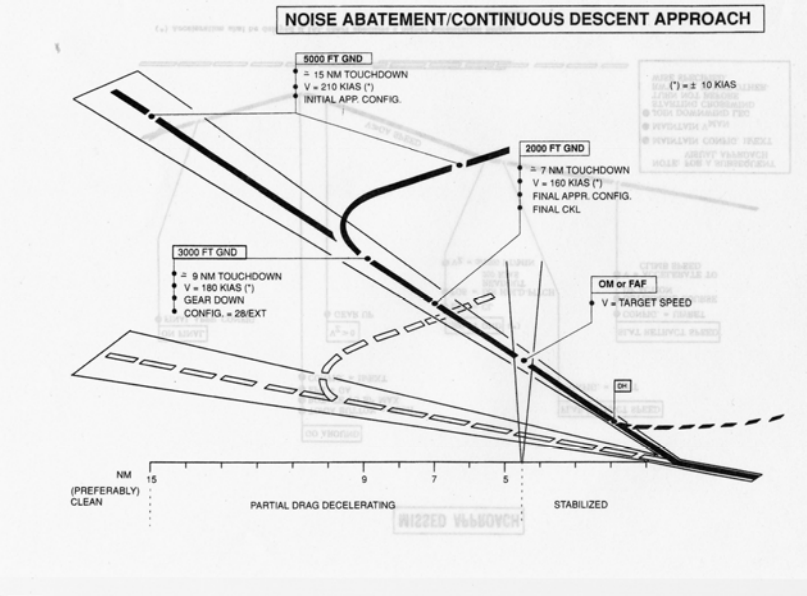


Figure 22: CDA Procedure for MD-80 Aircraft. [Reproduced With Permission of Alitalia Airlines. Not to be used for navigation.]

In non-precision approach procedures, because only horizontal navigation and guidance relative to the runway centerline is provided, on Jeppesen charts vertical checkpoints are often provided by strips that contain altitudes at specific locations. For example, in the approach to runway 23R at Dusseldorf Airport in Germany (see Figure 23) where the horizontal navigation and distance from the runway are provided by a VOR and a DME, and the vertical guidance information is in the strip with altitudes as specific DMEs. By cross checking the DMEs with the altitudes and making corrections to altitude deviations, pilots reset the growth in the uncertainty and reinitialize the altitude, and thus, ensure that the aircraft is neither too low nor too high off the desired vertical flight path. In precision approach procedures, crosschecking altitudes with DME distances is also common. For example, during an ILS approach, pilots crosscheck altitude against distance with the information in the approach chart, and some airlines use the outer marker crossing altitude as a vertical check.

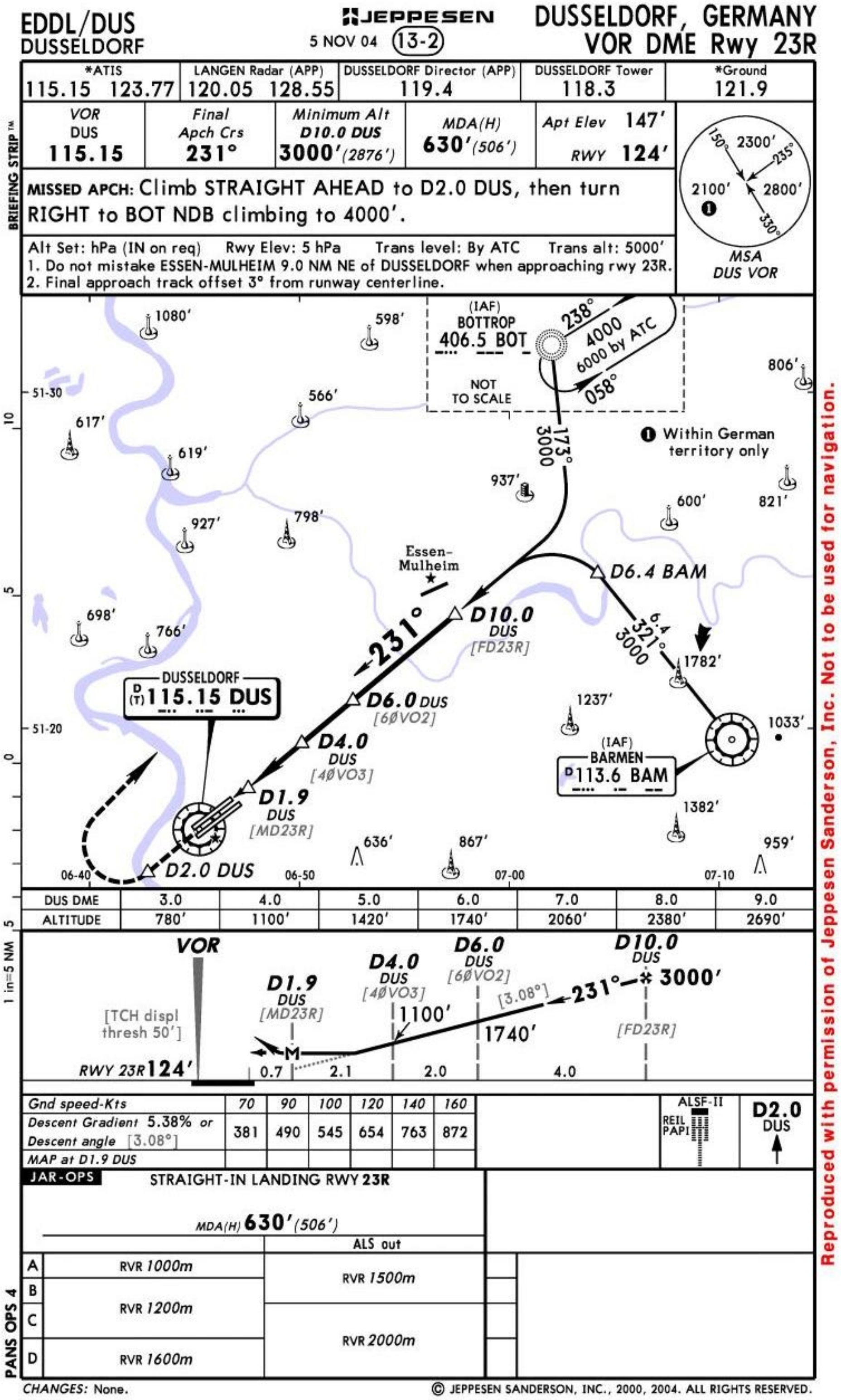
These examples suggest that the practice of imposing rules by having pilots manually cross-checking flight parameters (speed, altitude, and distance from the runway threshold) to ensure that the aircraft stays on the intended trajectory is familiar to pilots, and thus, that the use of gates as a feedback mechanism to manage the speed and achieve the target in ANAAPs does not present a significant learning leap for pilots. It is also important to note that the gates are intended to work for aircraft with two pilots. For single-pilot aircraft, the gates are likely to impose high workload on the pilot, and, thus, their usage would need to be further studied in such case.

4.2. An Experiment for Design and Evaluation of Gates

4.2.1. Objectives and hypotheses

In order to explore the utility of gates and gain insights into how they may be used as a means to manage the deceleration of ANAAPs without adding cockpit automation, an exploratory, part-task simulator experiment was conducted to design and evaluate the gates as a new cueing system for pilots. Specifically, the goal of the experiment was to examine the following questions:

1. **What is the performance?**
    a. What is the target achievement performance when no information (neither a flap schedule nor gates were provided), just the flap schedule, or gates and the flap schedule are provided?
    b. How does the target achievement change as the number of gates increases?
    c. How well can pilots achieve the target with wind uncertainty?
2. **What are the considerations in gate design?**
    a. How many gates should be used?
    b. Where the gates should be placed?
    c. How far apart should the gates be?



EDDL/DUS
DUSSELDORF

JEPPESEN
5 NOV 04 (13-2)

DUSSELDORF, GERMANY
VOR DME Rwy 23R

*ATIS	LANGEN Radar (APP)	DUSSELDORF Director (APP)	DUSSELDORF Tower	*Ground
115.15 123.77	120.05 128.55	119.4	118.3	121.9

VOR DUS	Final Apch Crs	Minimum Alt D10.0 DUS	MDA(H)	Apt Elev / RWY
115.15	231°	3000′(2876′)	630′(506′)	Apt Elev 147′ RWY 124′

BRIEFING STRIP ™

MISSED APCH: Climb STRAIGHT AHEAD to D2.0 DUS, then turn RIGHT to BOT NDB climbing to 4000′.

Alt Set: hPa (IN on req) Rwy Elev: 5 hPa Trans level: By ATC Trans alt: 5000′
1. Do not mistake ESSEN-MULHEIM 9.0 NM NE of DUSSELDORF when approaching rwy 23R.
2. Final approach track offset 3° from runway centerline.

MSA DUS VOR

DUS DME	3.0	4.0	5.0	6.0	7.0	8.0	9.0
ALTITUDE	780′	1100′	1420′	1740′	2060′	2380′	2690′

Gnd speed-Kts	70	90	100	120	140	160
Descent Gradient 5.38% or Descent angle [3.08°]	381	490	545	654	763	872
MAP at D1.9 DUS						

JAR-OPS STRAIGHT-IN LANDING RWY 23R

MDA(H) 630′(506′)

		ALS out
A	RVR 1000m	RVR 1500m
B	RVR 1200m	
C		RVR 2000m
D	RVR 1600m	

PANS OPS 4

CHANGES: None.

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Figure 23: Crosschecking of Altitudes with DMEs in a Non-Precision Approach.

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 to present the gates and the flap schedule?
    c. How do pilot accept the gates method? How many gates pilot 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 the speed target error would be smallest when the maximum of three gates was used in no wind, and would increase in the following order:

1. With Flap schedule (FS) and 3 gates; FS and 2 gates; FS and 0 gate; and no FS
2. With no wind uncertainty; with wind uncertainty.

4.2.2. Experiment Design

4.2.2.1. Design of ANAAPs and gates

While the primary goal of this experiment was to design and evaluate the gates as a new cueing system for pilots, the interests of the system stakeholders -- residential community, pilot/aircraft/airlines, and controllers -- were also taken into account in the design of the approach procedure, the pilot procedure, and the gates. The ground track of the procedure, designed for runway 17R at Louisville Standiford International Airport (KSDF), is shown in Figure 24. For simplicity, a straight-in track was chosen. The ground track is defined by four waypoints, WPC07, WPD07, WPG07, and CDA07, which are 25.0 nm, 22.0 nm, 14.0 nm, and 5.6 nm from the runway threshold, respectively. The altitude profile and the baseline speed profile are shown in Figure 25.

The altitude profile consists of a level flight segment at 7000 ft, followed by a 2.3-degree flight path angle (FPA) segment from WPD07 to WPG07 and a 3-degree glide slope segment from WPG07 to the runway. Since this is a straight-in approach, the aircraft typically intercept the glide slope at 5400 ft. The shallower than 3-degree FPA segment from WPD07 and WPG07 was designed to ensure that the aircraft would not accelerate after starting its descent at WPD07. This is especially critical in the presence of a tailwind.

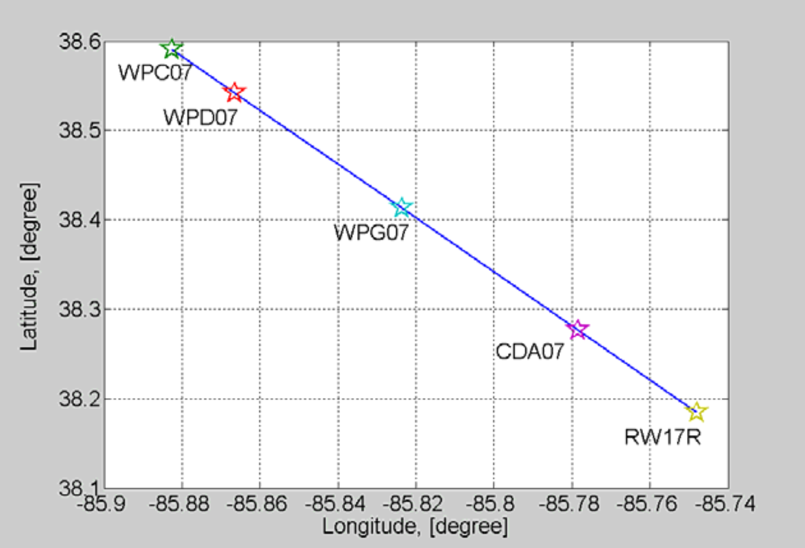

Figure 24: Waypoint Locations for Flight Track

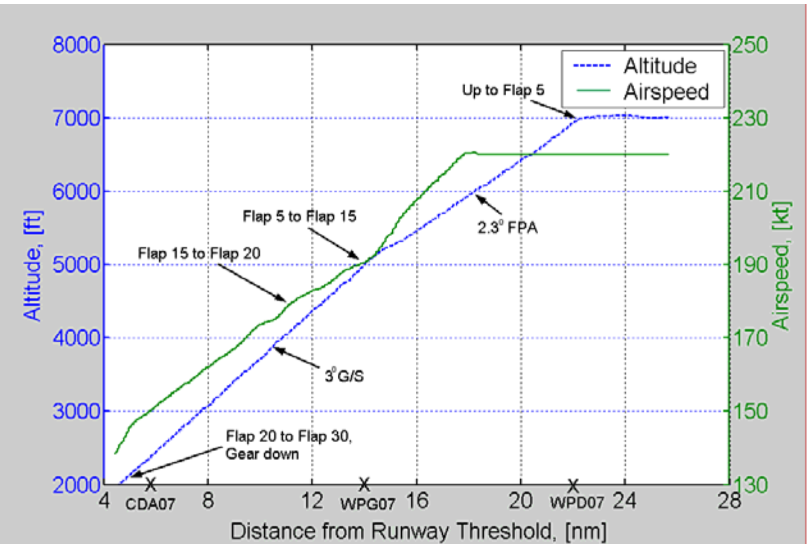

Figure 25: Altitude and Speed Profiles

The baseline speed profile features the aircraft flying at 220 knots starting from WPC07 (at 7000 ft) until reaching 6000 ft, at which point the thrust is reduced to idle and the flaps were extended to decelerate the aircraft to the target speed of 150 knots at the CDA07. The deceleration continues past CDA07 until the speed approaches the approach speed, at which point the auto-throttle increases the thrust to maintain the approach speed. The rationales for designing the speed profile and selecting its parameters are as follows. Using an initial speed of 220 knots balances the desire to keep the speed as high as possible for the minimization of the approach time and the need to have flap five extended for slowing down the aircraft. At 245000 lbs, the B767 would accelerate along the three-degree glide slope in a tailwind if the flap five were not extended. The maximum placard speed for flap five is 230 knots. The target speed of 150 knots at the CDA07 waypoint was chosen because this speed is in the middle of the range of the approach speeds of all types of commercial aircraft, and thus, can be used as a generic target speed for aircraft to achieve in preparation to meet the requirement of being fully stabilized and configured at 1000 AGL. The rationale for the placing the target at CDA07 (5.6 nm from the runway threshold) was that past this point in the descent, the noise impact could not be further reduced significantly by procedural changes. The CDA07 waypoint (CDAWP) typically corresponds to the outer marker or final approach fix at most airports.

To achieve the altitude profile and baseline speed profile, the procedure was designed in two steps. In the first step, a VNAV speed profile and a VNAV altitude path were created by adding altitude and speed constraints at the waypoints shown in Figure 24 and Figure 25. The constraints are listed in Table 3. The altitude constraints at WPD07 and WPG07 define the 2.3-degree FPA segment, and the altitude constraints at WPG07 and CDA07 define the three-degree FPA segment, which coincides with the three-degree glide slope. The speed constraint at CDA07 was added to create a constant VNAV speed profile from WPD07 to CDA07.

The second step entails using the Approach mode (APP), the Speed Intervention (SI) mode, and a gate cueing card for flap extension. The APP mode, armed at 6500 ft, was used to ensure that the aircraft captures both the localizer (which occurs instantly when the APP button is pushed because the aircraft is already aligned with the runway's center-line) and the glide slope (which typically occurs at 5400 ft). The SI mode, selected at 6000 ft, was used to dial the speed down to the approach speed of Vref30 + 5, and thus, bring the thrust to idle. To help pilots achieve the target speed of 150 knots 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. In this procedure, the gate cueing cards system consists of three gates placed at approximately every 1000 ft along with a recommended flap schedule as shown in Table 4. While adding more gates at smaller altitude intervals, such as every 500 ft, would provide pilots more information, it was believed that an increase in the number of gates would increase the pilot workload and consequently become intrusive. The requirement of extending flap five by WPD07 was designed to ensure that as the aircraft descends from WPD07, it would have enough drag to decelerate, especially in tailwind conditions.

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 220 kt	At 2350 ft

Table 3: Speed and Altitude Constraints

Gate (Altitude/Speed)	Recommended Flap Schedule
	Flap 5 by WPD07 (mandatory)
5000 ft / 190 kt	Flap 15
4140 ft / 180 kt	Flap 20
3000 ft / 160 kt	

Table 4: Gates and Recommended Flap Schedule

As shown in Table 4, the gates and the corresponding flap schedule were chosen so that after dialing down the 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 will be higher than 190 knots at 5000 ft, the pilot could extend flap 15 before 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 or extend flap 30 prior to CDA07 (gear and flap 30 were allowed to be extended at 2250 ft), use the speed brake, adjust the thrust, and retract an extended flap[10]. 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 mean that if the speed is fast as the aircraft approaches CDA07, and flap 25 is already extended, there is nothing the pilot can do to reduce speed; similarly, if the speed is slow as the aircraft approaches CDA07, the speed cannot be increased because the pilot is not allowed to increase thrust. When the speed reaches the approach speed, the auto-throttle increases thrust to maintain the approach speed.

4.2.2.2. Pilot Procedure with Gate Cueing Card

To implement the approach procedure, the following instructions were developed and given to pilots:

- Initial Conditions: 7000 ft, 220 knots, auto-throttle, flap 0
- LNAV and VNAV are initially engaged
- Extend flaps to have Flap 5 @WPD07
- At 6500 ft, arm approach (APP) to transition LNAV/VNAV mode to LOC and G/S capture mode. (VNAV remains engaged until G/S is captured)
- At 6000 ft, push speed intervention and dial MCP speed to the final approach speed Vref30 + 5. (VNAV mode transitions to speed hold mode).

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[10] Some airlines discourage pilots retracting an extended flap because the retraction may incur mechanical jamming.

- Use flap schedule and gates, if provided, to extend the flaps to achieve the EXACT speed of 150 knots at CDA07 waypoint.
- At 2200 MSL, lower gear[11].
- After gear is down, extend flap 30

An abridged version of these instructions was also displayed in a card as shown in Figure 26. This prototype card was designed to present information in a way that is easy to read and understand. The high usability was achieved by placing information and instructions in "briefing boxes" that are organized in the Volpe chart format [Osborne 1995] (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 Figure 26, the card's first box contains information on the airport (KSDF), the runway (17R), the aircraft weight (245000 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 WPD07, flap five be extended and the auto-throttle is on. The second column specifies that at 6500 the APP mode be armed. The third column specifies that at 6000 ft, the 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 knots at 2350 ft (CDA07 waypoint), and the instructions to lower the gear and extend flap 30 at 2250 ft.

4.2.2.3. 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.

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[11] This is the typical altitude at which pilots lower the landing gear to account for gear failures.

Independent Variables:

1. Feedback mechanism
    a. No Flap Schedule and no gates (NFS-0G)
    b. Flap Schedule without gates (FS-0G)
    c. Flap Schedule with two gates (FS-2G)
    d. Flap Schedule with three gates (FS-3G)
2. Wind uncertainty
    a. No Wind (NW)
    b. Tailwind (TW)
    c. Headwind (HW)

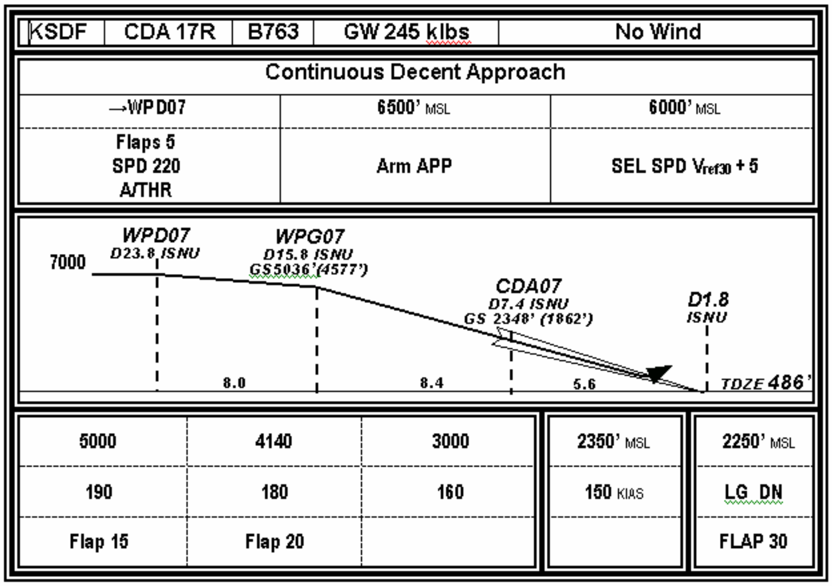

Figure 26: A Gate Cueing Card Prototype.

The four treatments of the feedback mechanism were designed to represent the different degrees of procedural information in the gate cueing card available to pilots: a) NFS-0G: No flap schedule and gate information available, the pilot on his/her own has to determine a flap schedule to decelerate the speed to 150 knots; b) FS-0G: Only the recommended schedule based on the no wind condition was provided; c) FS-2G: Two gates, at 5000 ft and 3000 ft, were provided with the recommended flap schedule; d) FS-3G: All three gates at 5000ft, 4140ft, and 3000 ft were provided with the recommended flap schedule.

The three treatments of the wind uncertainty were designed to represent the different levels of uncertainty in the wind condition. Since the baseline speed profile, gates, and recommended flap schedule were designed based on the NW condition, in the HW and TW approaches the pilot has to use the gates, if available, to adjust the flap schedule. For simplicity, the HW and TW profiles were designed to have a constant magnitude of 15 knots at 7000 ft, and thereafter the magnitude decreases linearly to 10 knots at the surface. While the TW magnitude is the maximum tailwind allowed for landings, the magnitude of the headwind can be greater in practice because most of the landings are into a headwind. If a greater than 15-knot HW were used in this experiment, the aircraft would decelerate to 150 knots without any flap, and consequently the thrust would need to be engaged to maintain the speed.

The test matrix was a 3 x 4 repeated-measures design in which each subject flew all 12 experimental conditions. The repeated-measures design has the advantage of using fewer subjects and allowing the comparison of each subject's performance across all conditions. However, this design also has some disadvantages. Flying all conditions can be demanding on subjects, and consequently may result in boredom, fatigue, undesirable trial run ordering effects, and learning effects. As mitigation measures to fatigue and boredom, subjects were frequently given breaks and ten airports with different field elevations were used. The ten airports included Raleigh County Memorial Airport (KBKW, 2468' field elevation), Dallas Love Field Airport (KDAL, 485' field elevation), Four Corners Regional Airport (KFMN, 5506' field elevation), Jackson Hole Airport (KJAC, 6447' field elevation), Los Angeles International Airport (KLAX, 101' field elevation), Eastern Oregon Regional Airport at Pendleton (KPDT, 1483' field elevation), Phoenix Sky Harbor International Airport (KPHX, 1115' field elevation), Provo Municipal Airport (KPVU, 4497' field elevation), Louisville Standiford International Airport (KSDF, 486' field elevation), Salt Lake City International Airport (KSLC, 4222' field elevation), and Luis Munoz Marin International Airport (TJSJ, 10' field elevation). Because the characteristics of the baseline altitude profile (in Figure 26) were kept the same for all approaches into these airports, the approaches into these airports have odd altitudes (rounded to tens of feet) in the level flight segment as well as at the points where subjects arming APP and dialing down MCP speed. All CDAWPs were placed approximately 5.4 nm from the threshold.

To offset ordering effects, counter balance trial runs, and reduce learning effects, the trials were first randomized and then selected so that these two criteria are met: 1) the first and last six trial runs each contains two HW, two TW, and two NW approaches; and 2) trial runs one through four, five through eight, and nine through twelve, each contains one NFS-0G, one FS-0G, one FS-2G, and one FS-3G cue. The first criterion ensures that the first six runs are balanced as a time reversal of the last six runs. The second criterion ensures that subjects were evenly exposed to the four feedback mechanism treatments every four runs. The randomization provides unbiased assignment to conditions so that each subject flew all twelve conditions in different orders.

4.2.2.4. Measurements and Performance Metrics

Two types of measurements were taken: aircraft states and subjective questionnaires at the completion of the experiment. Aircraft states included time, position (range, latitude, longitude, 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 the CDAWP, the change to the flap schedule by pilots, the 55-dbA contour noise footprint area, 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. Copies of these questionnaires can be found in Appendix C. These questionnaires contained questions regarding: pilots' strategies 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. To help prevent subjects from being biased by the content of specific questions, the open-ended questions were administered first, followed by the more specific closed questions.

4.2.2.5. Simulator Facility

The simulator facility is shown in Figure 27. The hardware consists of a desktop Pentium III computer with two 20” 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 consists of the Microsoft Flight Simulator (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 accurate representation of the actual B767 cockpit and its FMS.

Because the deceleration segment required high fidelity aircraft dynamics, the simulator was validated in two different ways. The first was by flying the simulator and comparing its aerodynamic data (vertical speed versus airspeed in different configuration settings) with those of an actual B767. The comparison showed that the 767 PIC closely mimics the behavior of an actual B767. 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 the behavior of the FMS had to be realistic.

Figure 27: Simulator Setup.

4.2.2.6. Protocol

The experiment was conducted at the MIT International Center for Air Transportation. Each subject took approximately 3.5 hours to complete the experiment. At the beginning of the experiment, subjects were asked to read and sign a “Consent to Participate in Non-biomedical Research” form approved by the Committee On the Use Humans as Experimental Subjects at MIT. Then 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 closely they were to the speed of 150 knots at the CDAWP. Subjects were also told that there was no preference for them being faster or slower than 150 knots. In addition, subjects were also given the following instructions:

- Follow the provided pilot procedure. If a procedural error is made, the approach will be rerun.
- All trial runs have the same aircraft weight of 245000 lbs.
- If speed reaches approach speed (Vref30 + 5) prior to the CDA gate, the auto-throttle will increase thrust to maintain speed. No penalty point will be counted for this.

- Once flap 25 is extended, if the aircraft is still fast approaching the CDA gate, then the subject must "live with it."
- Do observe and comply with placard flap speeds and minimum maneuver speeds.
- For experimental purposes, dialing 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 audible ground warning alarm (the alarm would go off in an actual B767).
- Do not use the speed brake.
- Do not retract an extended flap.
- Do not manually reduce thrust to idle or turn off auto-throttle.
- Do not arm approach before the descent waypoint (WPD07).
- 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 last flown on a real B767 on an average of four days before (the minimum was two hours and the maximum was two weeks).

4.2.2.7. Subjects

Only active B767 airline pilots with Air Transport Pilot rating were recruited for the experiment because of the their familiarity with the B767 deceleration performance, especially the aircraft decelerations at different flap settings. All fifteen participants – two chief pilots, seven captains, and six first officers -- were volunteers from Alitalia Airlines, American Airlines, UPS, United Airlines, and US Airways. Their flight experience ranged from 4500 to 19800 hours, with a mean of 10456 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 UK and other airports in Europe.

4.2.3. 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. Complete details of ANOVA results, including the validation of ANOVA assumptions, are presented in Appendix C. The results of the subjective open-ended and closed questionnaires are also presented throughout this section according to the topic under discussion.

4.2.3.1. Performance in Terms of Achieving 150 Knots at CDAWP

Because a focus of this experiment was to determine how well pilots can achieve the speed of 150 knots at the CDAWP with no preference for being faster or slower than 150, the performance metric is, therefore, defined as the absolute speed deviation between the aircraft's speed and 150 knots at the CDAWP.

<u>The Effect of Feedback Mechanism (FM):</u>

The boxplot[12] of the speeds at the CDAWP is shown in Figure 28. In all wind conditions, the speeds at CDAWP tend to get closer to the target speed, 150 knots, as the FM level increases. In addition, in no wind, the speed appears to evenly scatter around 150 knots. In the tailwind conditions, the speed tends to be above 150 knots because the tailwind tends to cause the aircraft

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[12] 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 lines extending from the inter-quartile range.

to arrive at the CDAWP earlier and with a higher groundspeed (and vice versa is true for the headwind conditions).

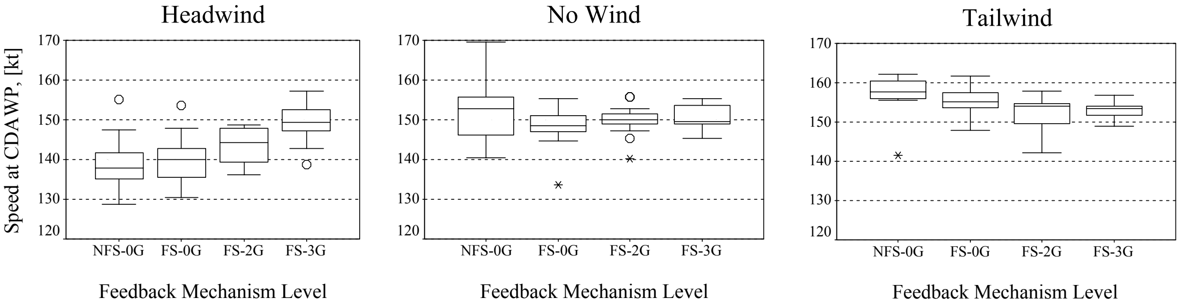


Figure 28: Boxplot of the Speeds at the CDAWP. O and * symbols denote outliers.

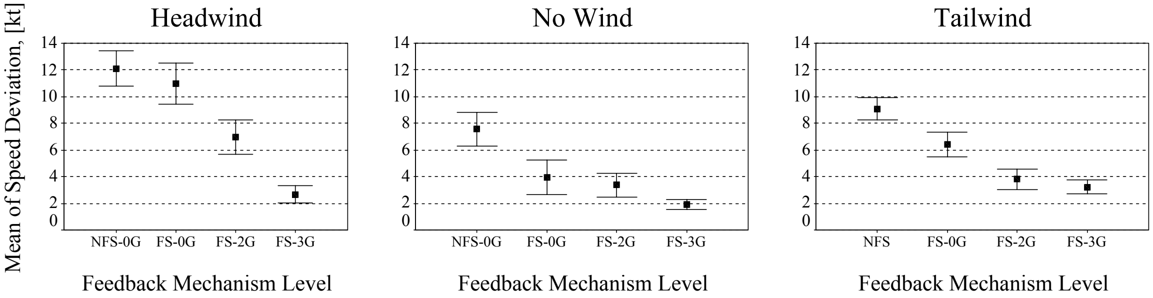


Figure 29: Feedback Mechanism Effect on the CDAWP Speeds for Each Wind Condition. Mean of Speed Deviation with ± 1SE for Each Wind Condition.

The means of the speed deviations at the CDAWP and the one standard error (SE) of the corresponding means are shown in Figure 29 for each wind condition and in Figure 30 for all wind conditions. Note that all speed deviations were kept positive because pilots were asked to be as close as possible to the target speed of 150 knots at the CDAWP with no preference for being faster or slower than 150 knots. As shown in Figure 29 and Figure 30, increasing the number of gates improved the ability of pilots to achieve 150 knots at the CDAWP in all wind conditions. The improvement is approximately two knots for every additional gate. Pair-wise 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.

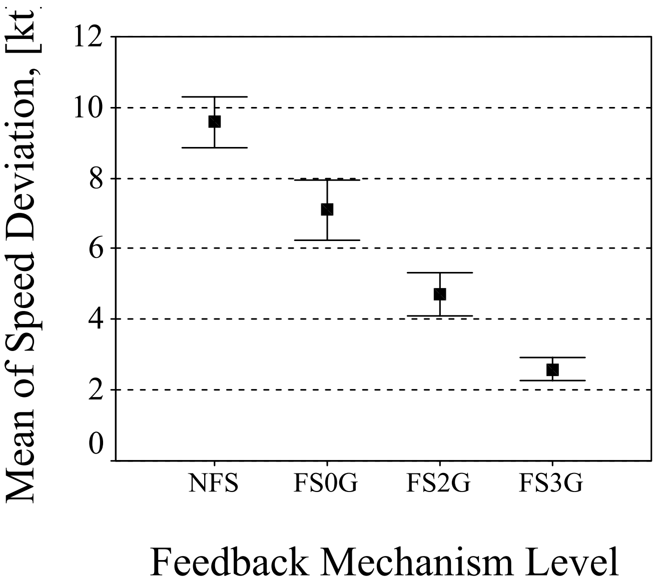


Figure 30: Feedback Mechanism Effect on the CDAWP Speeds. Mean of Speed Deviation with ± 1SE for Each FM in All Combined Wind Conditions.

<u>The Effect of Wind</u>

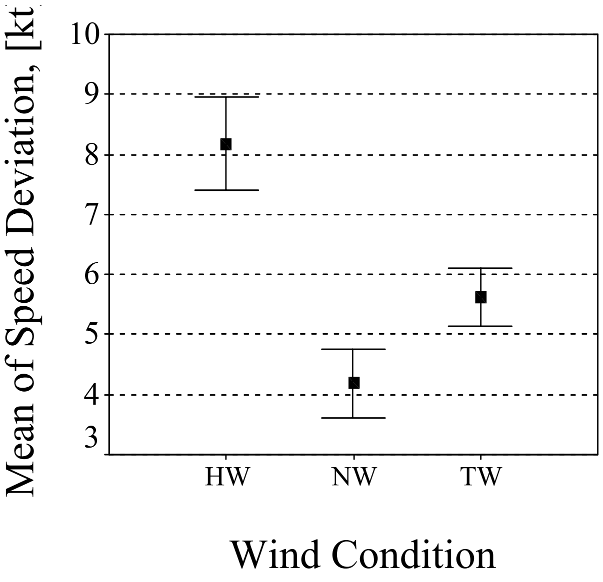


Figure 31: Feedback Mechanism Effect on the CDAWP Speeds. Mean of Speed Deviation with ± 1SE for Each Wind Condition with All FMs Combined.

The means of the speed deviations at the CDAWP and the one standard error (SE) of the means in each wind condition with all FMs combined are shown in Figure 31. There were two main significant 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 a number of pilots' comment 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 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 the 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.

In tailwind and no wind approaches, pilots commented if the aircraft appears to be fast as it approaches the 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 the CDAWP too fast as evidenced in the lower mean of the speed deviation in TW and NW conditions than in the HW condition (See Figure 31).

Interaction Effects

The interaction between the feedback mechanism treatments and the wind treatments is depicted in Figure 32. There were significant interactions among the feedback mechanism treatments and the wind conditions for the followings:

1. *FS-3G vs. NFS, HW vs. NW ($p < .088$):* In this contrast, the FS-3G compared to NFS, when HW is used compared to NW, is examined. This contrast is significant. The result indicates that the decrease in speed deviation found when NW is used

(compared to HW) is different when FS-3G is used compared to when NFS is used. In terms of the interaction graph (see Figure 32), it means that the distance between the triangle and the circle in the FS-3G condition (a small difference) is significantly smaller than the distance between the triangle and the circle in the NFS condition (a larger difference). Therefore, it can be concluded that the decrease in the speed deviation at CDAWP (or improvement in performance) due to NW (compared to HW) is significantly greater when FS-3G is provided than when NFS is provided.

2. *FS-3G vs. FS-0G, HW vs. NW ($p < .005$):* In this contrast, the FS-3G compared to FS-0G, when HW is used compared to NW, is examined. This contrast is significant. The result indicates that the decrease in speed deviation found when NW is used (compared to HW) is different when FS-3G is used compared to when FS-0G is used. In terms of the interaction graph, it means that the distance between the triangle and the circle in the FS-3G condition (a small difference) is significantly smaller than the distance between the triangle and the circle in the FS-0G condition (a larger difference). Therefore, it can be concluded that the decrease in the speed deviation at CDAWP (or improvement in performance) due to NW (compared to HW) is significantly greater when FS-3G is provided than when FS-0G is provided.
3. *FS-3G vs. NFS, HW vs. TW ($p < .017$):* In this contrast, the FS-3G compared to NFS, when HW is used compared to TW, is examined. This contrast is significant. The result indicates that the decrease in speed deviation found when TW is used (compared to HW) is different when FS-3G is used compared to when NFS is used. In terms of the interaction graph, it means that the distance between the triangle and the circle in the FS-3G condition (a small difference) is significantly smaller than the distance between the triangle and the circle in the NFS condition (a larger difference). Therefore, it can be concluded that the decrease in the speed deviation at CDAWP (or improvement in performance) due to TW (compared to HW) is significantly greater when FS-3G is provided than when NFS is provided.
4. *FS-3G vs. FS-0G, HW vs. TW ($p < .017$):* In this contrast, the FS-3G compared to FS-0G, when HW is used compared to TW, is examined. This contrast is significant. The result indicates that the decrease in speed deviation found when TW is used (compared to HW) is different when FS-3G is used compared to when FS-0G is used.

In terms of the interaction graph, it means that the distance between the triangle and the circle in the FS-3G condition (a small difference) is significantly smaller than the distance between the triangle and the circle in the FS-0G condition (a larger difference). Therefore, it can be concluded that the decrease in the speed deviation at CDAWP (or improvement in performance) due to TW (compared to HW) is significantly greater when FS-3G is provided than when FS-0G is provided.

5. *FS-3G vs. FS-2G, HW vs. TW* $p < .079$*):* In this contrast, the FS-3G compared to FS-2G, when HW is used compared to TW, is examined. This contrast is significant. The result indicates that the decrease in speed deviation found when TW is used (compared to HW) is different when FS-3G is used compared to when FS-2G is used. In terms of the interaction graph, it means that the distance between the triangle and the circle in the FS-3G condition (a small difference) is significantly smaller than the distance between the triangle and the circle in the FS-2G condition (a larger difference). Therefore, it can be concluded that the decrease in the speed deviation at CDAWP (or improvement in performance) due to TW (compared to HW) is significantly greater when FS-3G is provided than when FS-2G is provided.

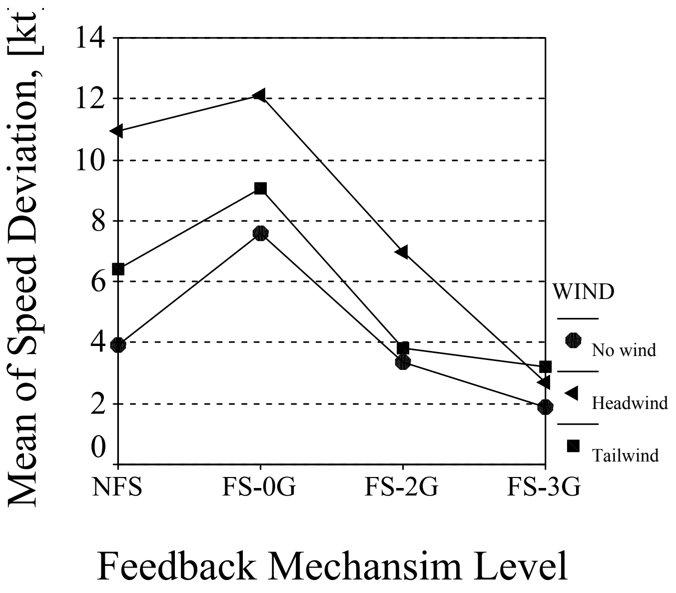


Figure 32: Interaction Between Wind and Feedback Mechanism Treatments

4.2.3.2. Noise Impact Performance

The mean and one standard error of the 55-dbA contour noise footprint areas for experimental conditions are shown in Figure 33. As expected, there was no substantial improvement in the noise reduction because all of the procedures flown in the experiment were noise abatement approach procedures, in which the thrust remained idle for most of the descent. The best noise reduction condition was the 3-G and No Wind condition, where pilots consistently approach the target speed without early thrust engagement.

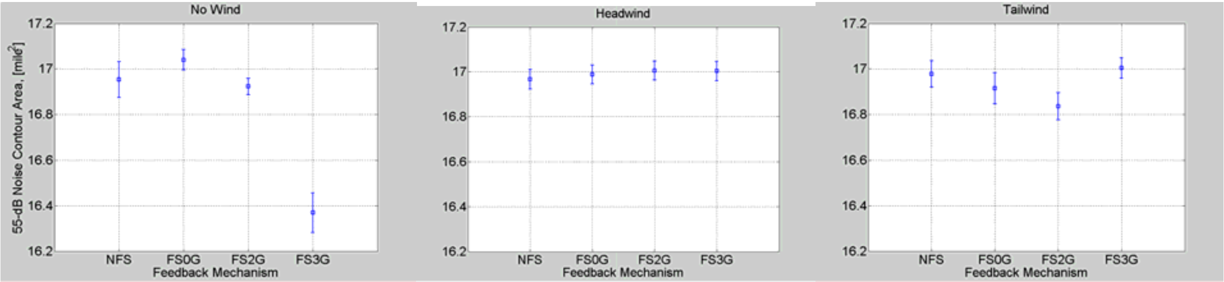
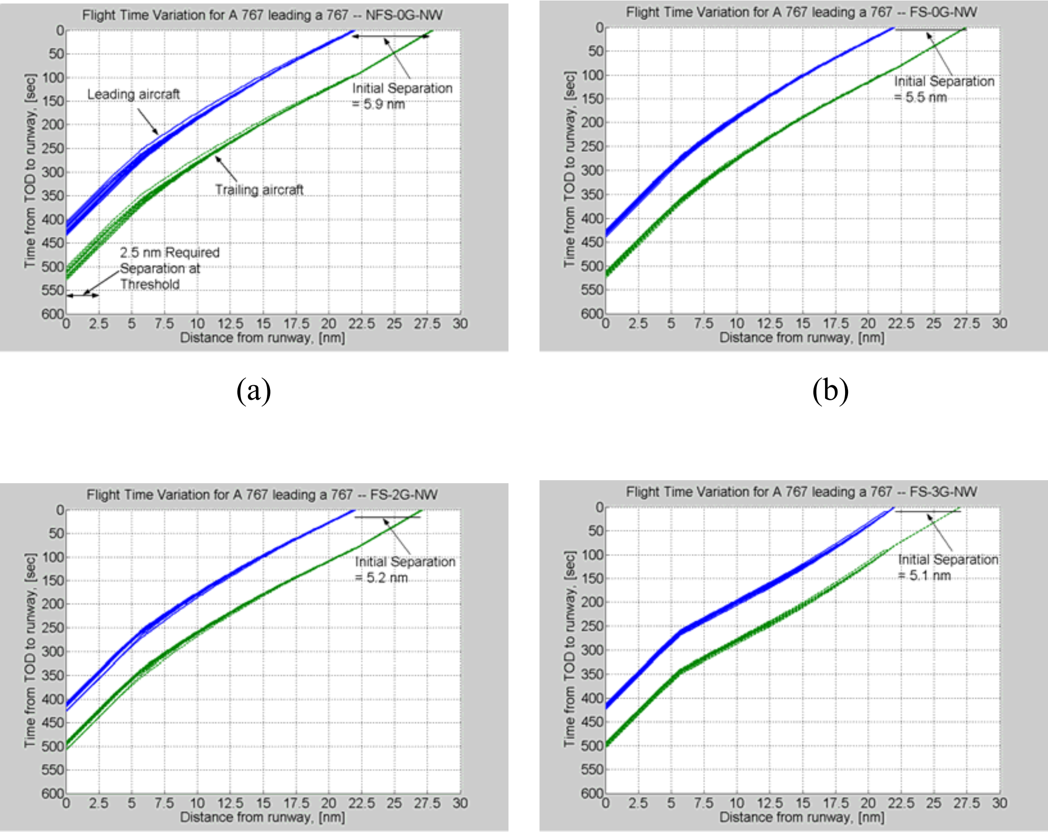


Figure 33: Mean and 1 SE of 55-dB Noise Contour Area

4.2.3.3. Time Variation and Runway Capacity Analysis

The flight time variation for the No Wind condition for different levels of feedback mechanism is shown in Figure 34, where each curve in the plot represents the flight time for a subject. To compute the capacity for the case where a B767 follows another B767, initial separation between the two aircraft was obtained by shifting the bundle of the top curves down in time so that a minimum required separation of 2.5 nm is met when the leading aircraft reaches the threshold. The bundle of the curves for the trailing aircraft was also added a constant flight segment at 220 knots prior to reaching the TOD. As shown in the figures, as the number of gates increase, the initial separation decreases because the pilots can fly more a more consistent profile with more gates. This decrease in the required initial separation means that the runway capacity would become higher as shown in Figure 35, where the capacity increases approximately by 7 aircraft per hour when 3 gates was used as opposed to no flap schedule and no gate. Similar results were also obtained for the headwind and tailwind cases.



(a) (b)

(c) (d)

Figure 34: Flight Time Variation for No Wind Condition.

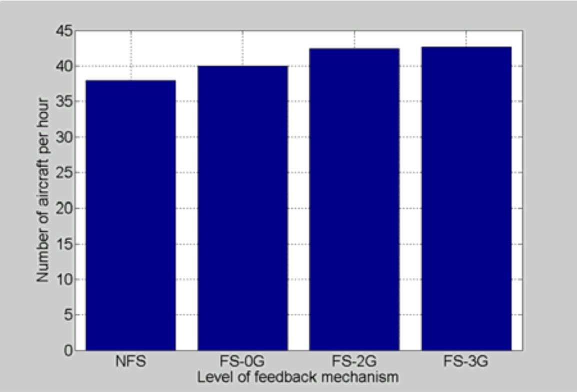


Figure 35: Runway Capacity for a B767 Following a B767.

4.2.3.4. Design of Gates for Decision Making Enhancement

<u>Usefulness of gates:</u>

As shown in Figure 36, most pilots felt that the gates were very useful for the management of the aircraft's deceleration and for achieving the target speed.

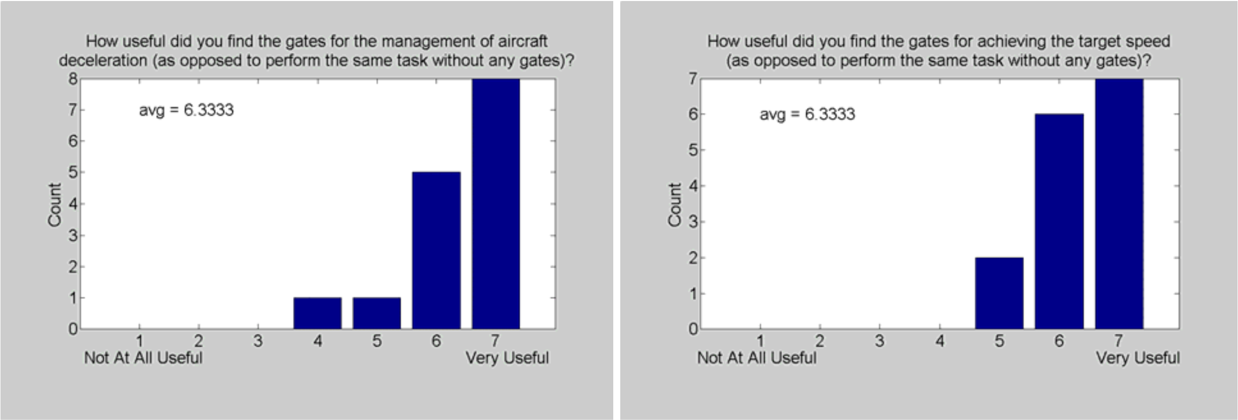


Figure 36: Questionnaire on the Utility of Gates.

<u>Number of gates:</u>

Consistent with the performance at the CDAWP, all pilots indicated that they preferred to have at least two gates as shown in Figure 37. However, there was a spread of opinion in terms of the number of preferred 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.

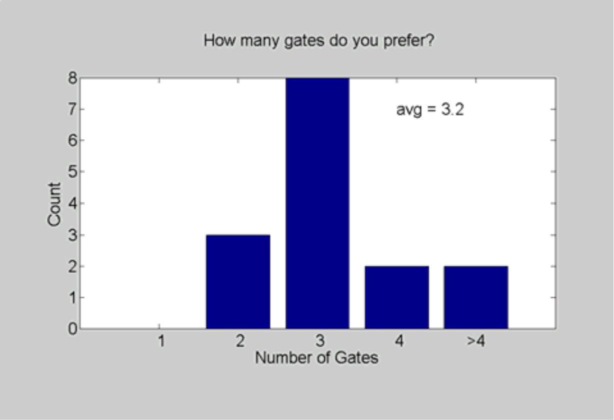


Figure 37: Number of Gates Pilots Prefer

Comparison of usefulness of first and last gates:

As shown in Figure 38, the pilots were evenly divided about the usefulness of the first and last gates. Pilots who thought the first gates were more useful justified their opinion by noting that the earlier the speed deviations were detected, the sooner the corrections could be made. Thus the first gates were important in providing guidance for flap extensions and setting up for a successful approach. Pilots who thought the last gates were more useful explained that where they started was not as important as where they arrived. Specifically, they felt that it was more important to reach the target (than the early gates), hence, they relied more on the speed deviations at the last gates to make final adjustments to the flap schedule. Finally, the justification for the first gates being as useful as the last gates was a combination of opinions of the other two groups of pilots: the need to start looking for trends in the early gates was as important as the need to rely on the last gates to make final adjustments.

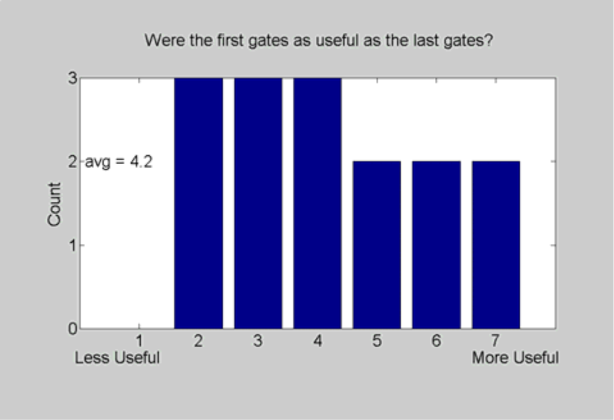


Figure 38: Comparison of the Usefulness of Last Gates and First Gates

Placement of gates:

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 knots at the target.

4.2.3.5. Objective Assessment of Pilot Strategy in Using Gates

Recall from Figure 26 that when the recommended flap schedule and the gates were provided, pilots adapted the flap schedule based on their projection and observation of the speed deviation at the gates. In order to gain insights into how pilots adapted to the gates, the adjustment that the pilots made to the flap schedule in response to their projection or observation of the speed deviations at the gates is shown in Figure 39 for the no wind, headwind, and tailwind conditions. As shown in Figure 39(a) for the no wind case, the pilots seemed to hedge on the early flap extension for the first gate, extending the flap earlier than recommended and consequently arriving slow at the first gate. The pilots then either delayed the flap extension when the aircraft was slow at the second gate or extended the flap early when the aircraft was fast, and the data suggest that for a one-knot deviation at the second gate, a two-knot adjustment was made to the flap schedule. Finally if the aircraft was still fast at the third gate, the pilot extended flap 25 attempting to slow down the aircraft to the target speed at CDA07[13].

For the headwind case shown in Figure 39(b), the pilots appeared to recognize that the headwind would provide extra deceleration to the aircraft, so they delayed the flap extension, even when the aircraft was fast at the first gate. The pilots also delayed the flap extension in a similar manner when the aircraft reached the second gate, although the adjustments in delaying the flap extension were larger than those adjustments at the first gate. One plausible reason for this is that the pilots felt that they always had flap 25 as a safety net to increase the deceleration so they

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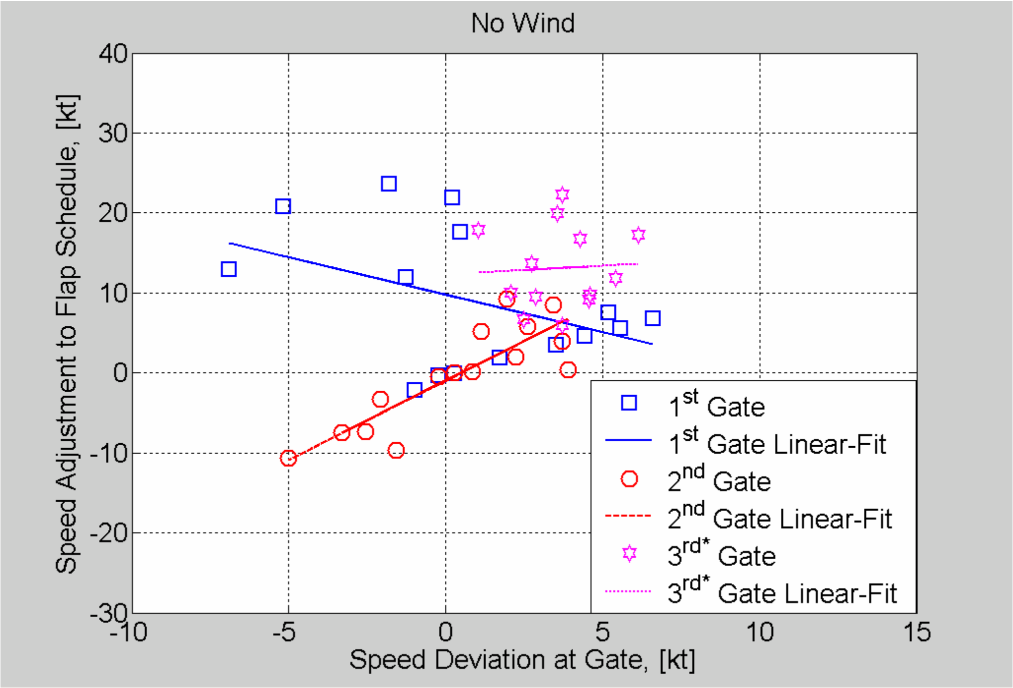
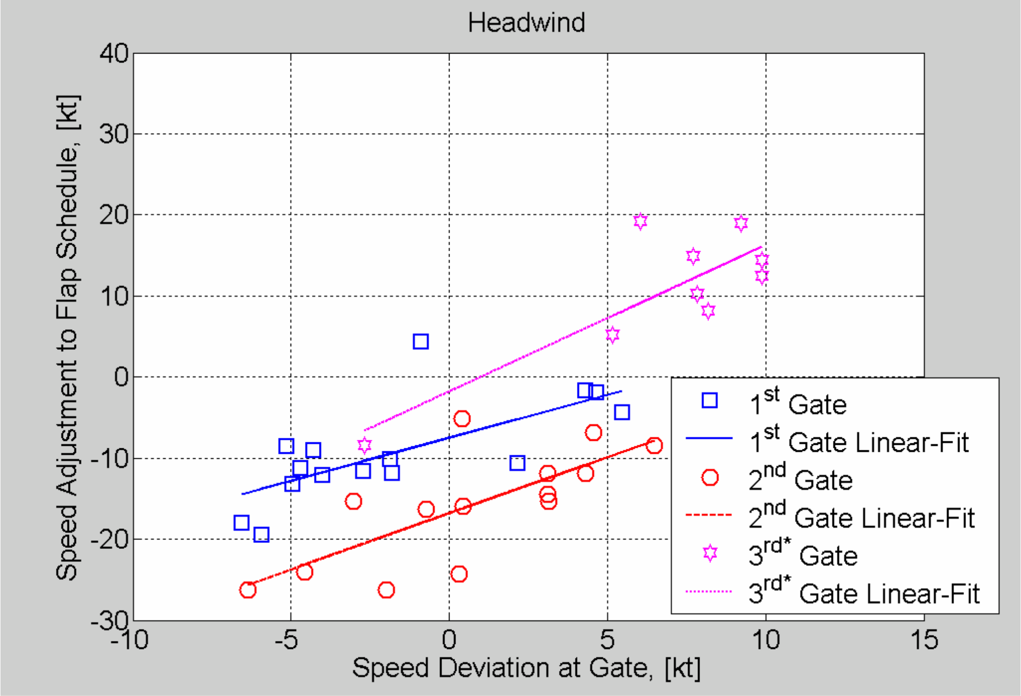
[13] Note that since a recommended speed was not provided for flap 25 or for the third gate, a baseline value of 150 knots was chosen as the recommended speed for flap 25 and for comparison purposes.

did not need to be aggressive at the second gate. Finally if the aircraft was fast when reaching the third gate, the pilots used flap 25 to provide additional deceleration.

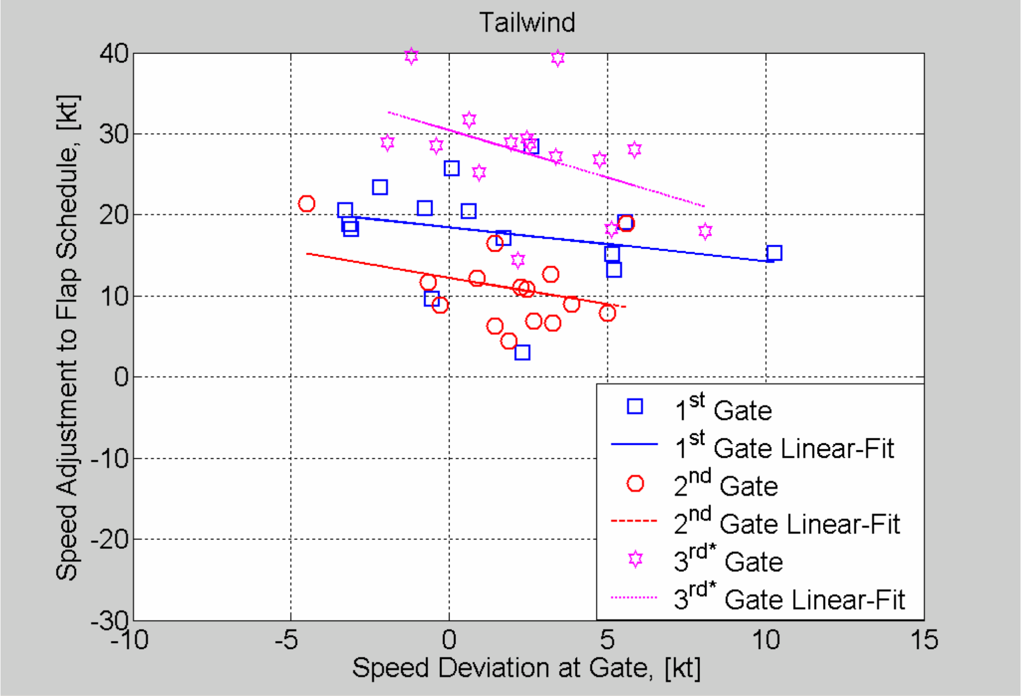
For the tailwind case shown in Figure 39(c), the pilots seemed to hedge by extending the flap early for the first gate, regardless of whether the aircraft was slow or fast. The pilots probably felt that they needed to make sure that the aircraft would start slowing down early because the tailwind made it hard to increase the deceleration. This was also evident with the pilots extending the flap early even when the aircraft was slow when reaching the second gate, and almost every pilot used flap 25 because the aircraft was fast when reaching the third gate.



(a)



(b)



(c)

Figure 39: Pilot Adaptation to Gate Speed Deviations: (a) No wind; (b) Headwind; (c) Tailwind.

4.2.3.6. Subjective Assessment of Pilot Strategy in Using Gates

Pilots were asked to describe the strategy that they used to manage the deceleration and achieve 150 knots at the CDAWP for the following three conditions:

1. No flap schedule or gates were provided:

When neither the recommended flap schedule nor the gates were provided, each pilot was forced to develop his own strategy to achieve the target. The pilots' strategies can be broadly grouped into two categories: 1) gauging the deceleration and extending flaps without specific goals along the trajectory, and 2) gauging the deceleration and extending flaps in an attempt to meet the virtual goals that they created. Ten pilots' answers, which did not include specific numbers or rules of thumb to indicate how they anticipated the deceleration, were assigned to the first group; five pilots' answers, which contained specific numbers that they computed to guide their anticipation of the deceleration, were assigned to the second group. With the first category, nine pilots indicated that they gauged the deceleration of the aircraft based on one or a combination of the following parameters: altitude, speed, distance, air speed, ground speed, vertical speed, and rate of change of speed (versus altitude or distance); then they attempted to estimate the progress of the aircraft. One pilot guessed a specific flap schedule for each wind condition but did not provide any concrete numbers as a basis for the determined flap schedule.

With the second category, all five pilots indicated that they used rules of thumb based on their own computation to gauge the aircraft's deceleration. Three pilots commented that their goal was to manage the flap schedule so that the aircraft would lose the same amount of speed every 1000 ft. These pilots determined that in order to decelerate from 220 knots to 150 knots at the CDAWP, they would have to lose 70 knots (from 220 knots at the TOD to 150 knots at CDAWP) in 3450 ft (from 7000 ft at the TOD to 2350 ft at CDAWP), which is approximately equal to 20 knots for every 1000 ft. Another pilot also used this method, but, in addition, this pilot made his own gate at 1000 ft above the CDAWP. The fifth pilot did not use this method, but made his own gate at 2000 ft above the CDAWP and relied on the deceleration arrow to manage the deceleration.

The performance of the pilots in the two groups is shown in Figure 40. The pilots in the second group outperformed those in the first: They had an average speed deviation of 8.2 knots, whereas the ten pilots in the first group had an average speed deviation of 11.3 knots.

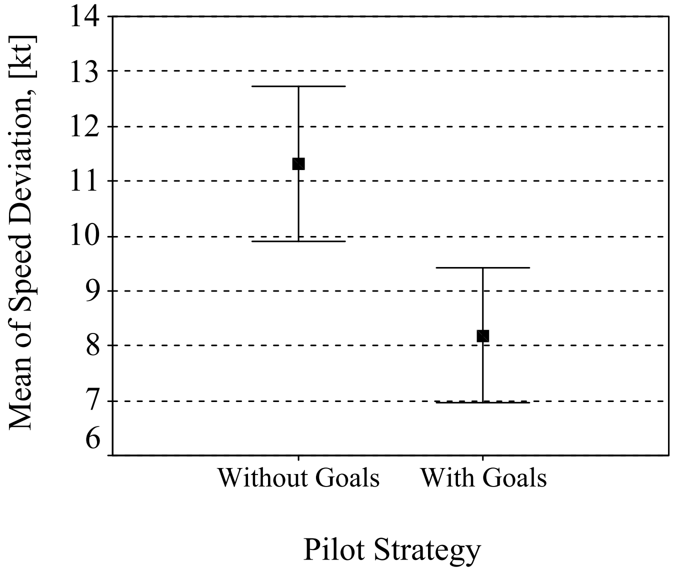


Figure 40: Mean of Speed Deviation ± 1SE for Pilots with Goals and No Goals When No Flap Schedule and Gates were Provided.

2. Recommended flap schedule was provided without gates

When a recommended flap schedule was provided, pilots commented that they used similar strategies to that of the case when the flap schedule was not provided, but they also used the recommended flap schedule as a reference to refine their techniques.

3. Recommended flap schedule was provided with gates

When the flap schedule was provided with gates, pilots commented that while tracking the speed profile, their projection of the speed at the next gate and the observation of the speed deviation when the aircraft was at that gate allowed them to detect whether the aircraft was fast or slow relative to the nominal profile, and to estimate whether the aircraft would reach the next gate with the current deceleration trend. Based on these judgments, they said they could either delay or expedite the next flap extension. Eight pilots felt that gates were very useful and simplified their task of managing the aircraft's deceleration and achieving the target easier.

4.2.3.7. Subjective Feedback on the Implementation of Gates

Because the scope of the experiment was limited to investigating the utility of the gates in a part-task simulator, many pilot tasks and elements (such as traffic or weather monitoring, communication with controllers or airlines operating centers, crew coordination, and checklists) that exist in the cockpit during a landing procedure were not included in the experiment. However, to facilitate further investigation on the potential implementation of the gates in actual operation, pilots were asked to provide feedback on the following:

Pilot Acceptance

As shown in Figure 41, overall there was high acceptance from pilots for the utility of the gates as a means to manage the aircraft's deceleration and meet 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 DMEs in a non-precision approach (see Figure 23). 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.

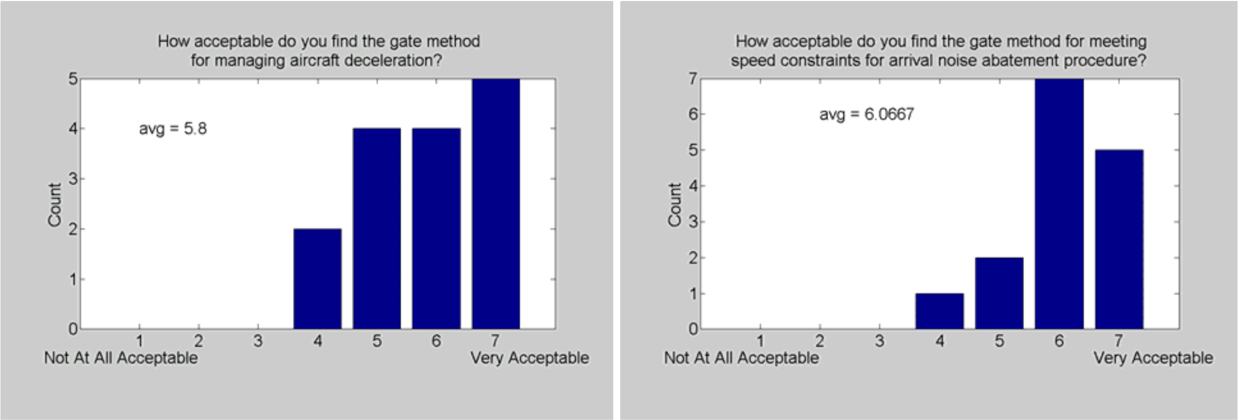


Figure 41: Pilot and Controller Acceptance

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.

Two pilots also warned that implementing gates could incur too many callouts and cause distractions for the crews (for a two-pilot procedure). As mitigation measures, the pilots suggest that "dialog boxes" articulating the crew's roles and verbal communication should be developed, and that the PF should provide the PM a briefing prior to the procedure to confirm their responsibilities.

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' FMS and Boeing's FMS have different protection schemes for this. Airbus' 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/airlines' rules, which specify the values at which flaps should be extended.

Second, seven pilots commented that additional noise impact must be accepted in order 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, which 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. While these measures are potentially viable, they deserve further investigation given the benefit of achieving more fuel-efficient and quieter approach of ANAAPs.

Format of gate card

As shown in Figure 42, pilot acceptance of the gates was very high. The pilots were asked to comment on several versions of the gates cueing card, and they preferred the version given in the experiment the most. They commented that the presentation of the given gate cueing card in general, and the gates and the recommended flap schedule in particular, was clear, simple to understand and read, and balanced in terms of the amount of information. The pilots also liked the sequential arrangement of information because they said that it is similar to the way information is presented in standard approach charts and allowed them to continuously and quickly verify and make comparison of parameters that are relevant to the flight progress. One pilot preferred to add some gate information to the profile view, although the majority of the pilots did not feel that this was necessary.

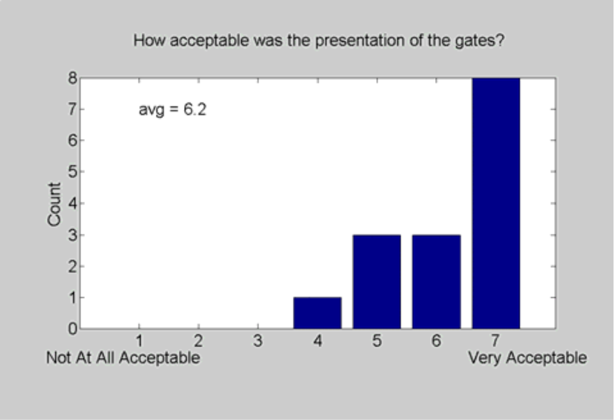


Figure 42: Acceptance of the Presentation of Gates

Crew Coordination in Cockpit

The pilots' opinions were 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 PF, the PM must be aware of the situation and keep of the PF informed the "big picture" of the operation. To accommodate this, six pilots suggested that the crew coordination should be similar to that of a non-precision approach: the PM monitors all aspects of the approach and makes callouts to the PF the deviations at the gates and the parameters of the next gate while the PF calls out his actions (such as requests for flap extension) when making adjustments to keep the aircraft as close as possible to 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 worthy of further investigation, as the results would provide additional insights into the way pilots manage the aircraft deceleration.

Workload

Although the experiment did not have many features of the actual cockpit environment, pilots' opinions on the potential workload that they might experience with gates in actual operation were solicited. As shown in Figure 43, a majority of the pilots felt that the task of managing the aircraft's deceleration and achieving 150 knots at CDAWP becomes easier when they were provided with more gates. Ten pilots explained that that they did not have to perform the mental "gymnastics" when they were provided with gates every 1000 ft.

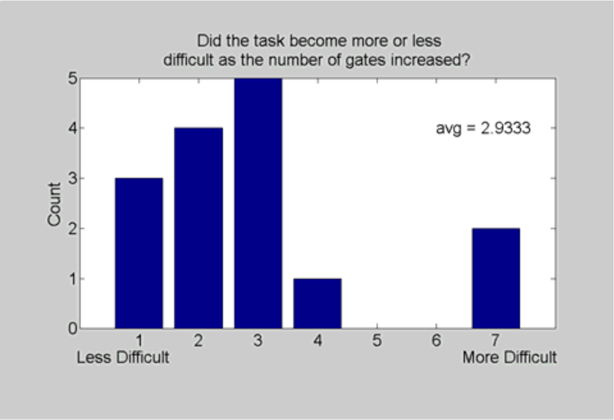


Figure 43: Task's Difficulty as Number of Gates Increased

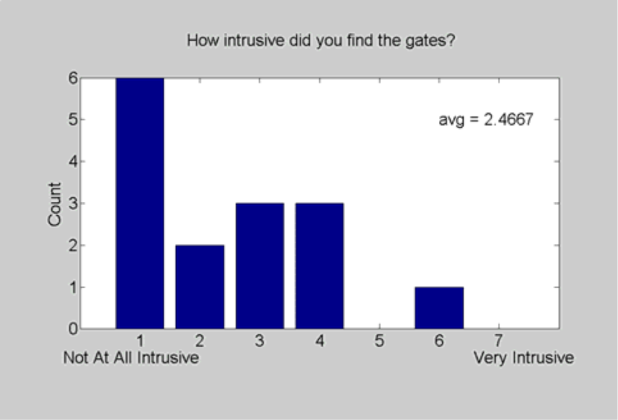


Figure 44: Intrusiveness of Gates

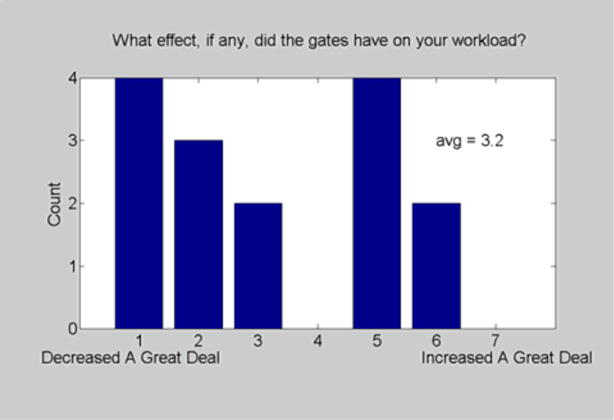


Figure 45: Effect of Gates on Workload

4.2.4. Discussion and Conclusions

It was anticipated that providing pilots with a nominal flap schedule and gates would improve the target achievement, and, in the presence of wind uncertainty, would help pilots 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 two knots. This markedly improved performance, however, may not imply that the speed target error can be driven to zero if more gates were provided for several reasons. One is that, as shown in the runway capacity analysis (see section 4.2.3.3), increasing the number of gates increases the runway capacity but provides diminishing returns at some point (i.e., the capacity improvement for using three gates is slightly higher than that of using two gates). Second, as many pilots indicated, having too many gates would be invasive and workload intensive, and, consequently, may force the pilot to refrain from using the gates.

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 of the deceleration) could slow down the aircraft too fast. This in turn made the aircraft reach the target speed prior to the target altitude, and, consequently, increased the noise impact because 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 in order to avoid early thrust engagement.

It was important to note that if the pilot could achieve the speed target at the CDA waypoint (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 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. While the exclusion of the use of the speed brake and thrust in this experiment was due to the increase in noise and other undesirable consequences as discussed in Section 2.1, it also implied that the results obtained this experiment (using the flaps alone) represent the performance with conservative control authority.

The experiment results also provided many important insights into the issues concerning the human factors aspects of gates implementation, the design considerations of gates, and the integration of gates into the cockpit. First, as anticipated, the way the pilots adapted the flap schedule based on their observation at the gates was 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 the gates 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 which 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 projection of the flight progress along with the gates, then the target achievement would improve. This strategy can be used in the 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.

Third, 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.

Fourth, there was a 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, but the pilots indicated that they had seen the gates in a different form (via non-precision 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.

Overall, the findings in this experiment, in particular the fact that the gates method was well received by the pilots and the markedly improved performance with gates, suggest that the gates are a viable concept that deserves further investigation in a more realistic environment with actual crew cockpit coordination, controllers, traffic, and weather. For implementation in the near future, the gates would be an enabling factor to achieve significant noise reduction in heavy traffic flows without adding additional aircraft automation. The issues involved in the integration of ANAAPs into the ATC system in general, and the gates into the cockpit in particular, will be discussed in the next chapter.

Another important implication from the findings in the experiment is that they reinforced the applicability of the underlying design principle that the growth in uncertainty in a system can be managed by providing specific, updated target states toward which the system should be controlled.

While these results support the notion that gates are a means to help 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 participated in the experiment were volunteers and were very enthusiastic about the prospect of implementing noise abatement approach procedures. Therefore, the results may be biased towards pilots favoring new pilot cueing systems for ANAAPs in a controlled laboratory environment.

5. Issues on the Integration of ANAAPs into the ATC System

The results in Chapters 3 and 4 showed that the aircraft delivery accuracy could be obtained by designing procedure parameters that are robust to uncertainties in pilot response time and the wind conditions, and by providing pilots with a simple cueing system that enhances their ability to manage the aircraft's deceleration. In this chapter, two main issues involved in the integration of ANAAPs into the ATC system are discussed. The first issue is the limitation of air traffic controllers in predicting future separation and maintaining it between aircraft, and the second issue is the heterogeneity in the ATC system components.

5.1. Controller Limitation

One of the primary obstacles to the widespread implementation of ANAAPs in the existing environment where air traffic controllers are responsible for the separation between aircraft is the difficulty that the controllers have in predicting the future separation between aircraft performing ANAAPs, and, therefore, in planning conflict free trajectories.

In the existing practice, to separate aircraft controllers typically employ speed as a surrogate for distance. That is, to maintain aircraft separation, controllers frequently place a series of aircraft at the same speed with the desired separation during the initial segments of the approach. From that point onwards, controllers maintain the aircraft at the commanded speed and use the range circles with radii of three or five miles on the radar map to monitor the separation. This technique is illustrated with a typical altitude profile flown by aircraft (see Figure 46) and standard step-down speed profiles used by controllers (see Figure 47). Since each speed profile is mostly made up of a series of constant speed segments, the evolution of the aircraft's distance from the runway can be approximated as a series of straight lines (see Figure 48).

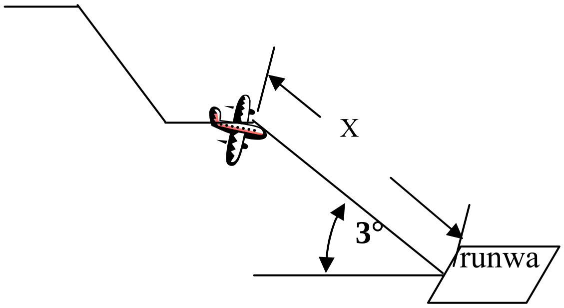


Figure 46: A Typical Step-down Altitude Profile Under Existing Procedures.

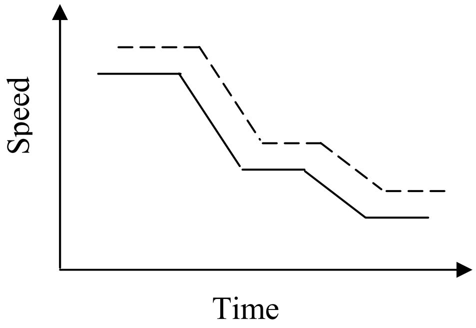


Figure 47: Typical Step-down Speed Profiles Under Existing Procedures

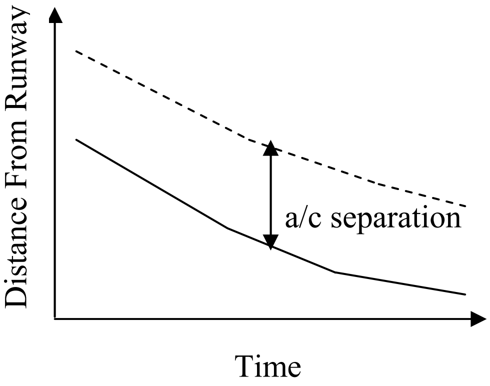


Figure 48: Separation Between Two Aircraft.

While this "command and control" methods is fundamental to the way controllers manage aircraft, the implementation of ANAAPs requires aircraft to decelerate continuously (see Figure 49) and, thereby, making the separation between the aircraft non-constant and nonlinear with time. As a result of this departure from the conventional method of controlling aircraft, it is only possible to achieve either moderate noise reduction in heavy traffic flows through a mostly manual procedure with high air traffic controller workload, or significant noise reduction in light traffic flows through a highly automated procedure that requires expensive aircraft automation. A case in point is the existing implementation of noise abatement approach procedures, in particular the continuous descent approach (CDA) procedure at London Heathrow Airport (and several other airports in Europe). As shown in Figure 50, aircraft performing CDA typically start the descent at 7000 ft and intercept the glide slope from below while continuously descending in altitude [Kershaw et al. 2000]. The CDA implementation involves controllers giving estimates of the distance to runway, and, based on this distance, the pilots use a lookup table to determine a rate of descent (or vertical speed) that minimizes level flight from descent clearance to glide slope interception. The vertical procedure of the CDA includes a 2.5 nm level flight segment joining the glide slope, and a CDA is achieved when the aircraft can descend from the TOD to the level flight segment before intercepting the glide slope. The 2.5 nm level flight segment is designed into the approach to provide a buffer for errors in the controller's estimate of the distance of the aircraft to the runway (an underestimate of the distance may cause the aircraft to intercept the glide slope from above or over fly the airport), to help aircraft slow down to meet ATC speed requirement, and to help controllers close up large gaps between aircraft. In addition, due to the lack of pilot cueing systems that would help cope with uncertainty in pilot performance and variability in the wind conditions, large initial separations between aircraft may be set up so that their separation would not decrease below the minimum required wake vortex separation throughout the approach.

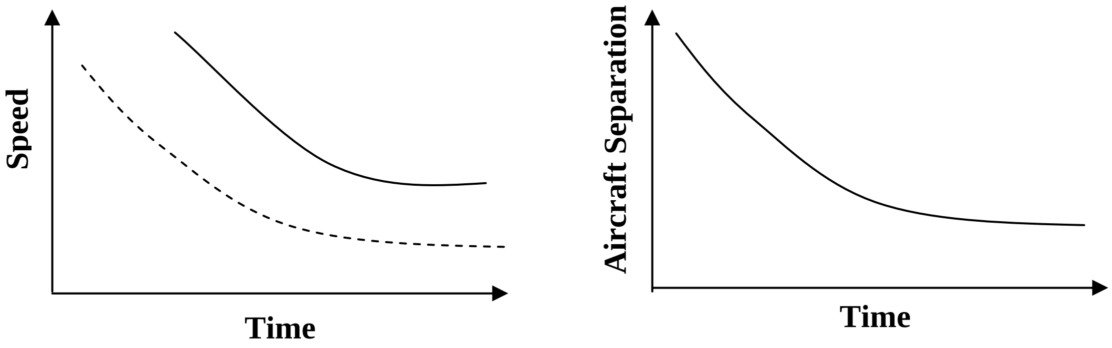


Figure 49: Example of Speed Profiles under ANAAP: Separation is Non-constant, Nonlinear With Time.

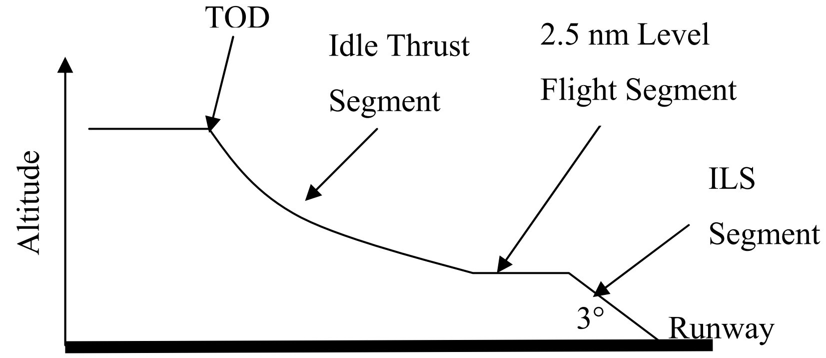


Figure 50: Vertical Profile of Existing CDA Implementing in Europe.

Given the results obtained in this thesis, it appears that the gates are worthwhile for further studies and would be an enabling factor to achieve significant noise reduction in heavy traffic flows without adding additional aircraft automation. The key to achieve this lies in the feature that the gates give the pilots the ability to adjust the nominal flap schedule, and thus 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 controllers command aircraft to fly similar speed profiles, albeit as a series of step-downs, aircraft performing ANAAPs can also fly similar speed profiles. 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.

5.2. Heterogeneity in System Components

Another important issue that must be considered in the integration of ANAAPs into the existing ATC system is the heterogeneity in the ATC system components. First, on the airborne side, while the effect of the variability in aircraft type, weight, and aerodynamics characteristics on the aircraft performance can be accounted for in the procedure and cueing system design as demonstrated in the work in this thesis, the variability of aircraft equipage is a harder issue to deal with. For instance, FMS logic designed by Honeywell works differently from those designed by Smiths Industry, and some aircraft (e.g., B727, DC10, DC9, B747-100,200,300) do not have VNAV capability.

The dissimilarities in aircraft equipage imply that not all aircraft can perform ANAAPs, and that the ATC system must be able to accommodate mixed procedures (ANAAPs and conventional approaches). Operating mixed procedures would require changes to the way controllers manage traffic. This issue can be investigated by studying a) whether controllers are able to sequence streams of aircraft performing ANAAPs and non-ANAAPs and to predict future minimum separation violations or excessive aircraft separation, b) whether controllers are able to develop an appropriate combination of control actions (e.g., extending trailing aircraft to longer paths and adjusting the speed) to resolve potential separation violations or excessive separation. Operating mixed procedures may also require changes to the airspace because of additional flight tracks or altitude levels for different approaches. While the structure and characteristics of the airspace around each airport are unique, a problem common for all airspace is that aircraft performing ANAAPs penetrate many altitude levels when they descend continuously from the TOD. The penetration of altitude levels causes two problems: it deprives controllers of the ability to separate aircraft by altitudes; and it may require sterilization or redesign of airspace to accommodate aircraft.

Second, on the groundside, the dissimilarities in the ILS and in the weather systems present significant challenges. ILS are typically an integral part of most airports, but the required area coverage of the lateral and vertical path for ANAAP application may be beyond the capability of the existing ILS equipment (the localizer and glide slope) or unavailable due to the lack of the equipment. Dissimilarities in the weather reporting systems available are also great. While the wind information along the flown flight track of each aircraft is currently available (via ACARS for relay to a central location on the ground) and can be combined with historical wind data to reconstruct the wind field in the terminal area, many airports do not have the tools on the ground to interact with ACARS and many airlines do not have ACARS installed for economic reasons.

These issues imply that changes to the ATC system for the implementation of ANAAPs will have to be an evolutionary process, and that in the near future the implementation of ANAAPs will be limited to airports or airlines with capabilities that are conducive to sidestep the issues mentioned in this chapter.

6. Thesis Contributions and Conclusions

Advanced noise abatement approach procedures enabled by flight guidance technologies such as GPS and FMS and auto-throttle have been shown to reduce operational aircraft noise on communities surrounding airports. To implement these procedures in the near future and fully achieve their benefits at airports with high traffic, it is necessary to overcome two challenges. One challenge is the mitigation of the adverse effects of system uncertainty (due to factors such as variability in pilot response and in the weather conditions) on the aircraft performance, and another is the inability of air traffic controllers to manually separate aircraft that are decelerating at different rates. The work in this thesis primarily addressed the first challenge through the development ANAAP designs and a new pilot cueing system. In addition, a design principle based on using rules/procedures to constrain the system behavior into desirable form was developed, and was validated in its application to the design of ANAAPs and the new pilot cueing system.

6.1. Development of Noise Abatement Approach Procedure Designs

To provide a baseline procedure for the work in the thesis, first, a definition of ANAAPs design parameters as well as the identification of the ANAAPs implementation challenges, sources of uncertainty, and system's stakeholders' objectives were developed. Second, a new formulation that treats certain parameters as strategic (parameters H_{TOD}, $V_{TOD,}$ V_F, $H_{F,}$ and H_I) and tactical (flap schedule K) control variables was synthesized as a tractable way for designing and analyzing ANAAPs. Under this formulation, sets of feasible flap schedules were first determined based on given values of the strategic control variables, and, then, were used to study the impact of delay in pilot response and wind uncertainty.

The impact of delay in pilot response was investigated by developing models for delay in pilot response and then using the models to optimize the procedure parameters through Monte Carlo simulation. Insights into the impact of uncertainty in pilot response were gained through a simulator-based, human factors experiment conducted at the NASA Ames CVSRF 747-400 Level-D full motion flight simulator with 16 active airline pilots. The goal of the experiment was to determine the characteristics of the pilot delay in extending flaps and to construct models of the pilot delay. In the experiment, the PFs and PMs were given a flap schedule and their delay in extending the flaps were measured. Experiment results showed that: 1) when the PF cues the PM to extend flaps, their average delay is 2.2 seconds with a standard deviation of 2.8 seconds; 2) when the PF cues the PM in turbulence, their average delay is 2.3 seconds with a standard deviation of 4.8 seconds; and 3) when the PFs extends the flaps themselves (without the help of PMs), their average delay is 3.2 seconds with a standard deviation of .46 seconds. These results were used to synthesize the models for pilot delay (with and without turbulence), but more importantly, they imply that in the procedure design, the pilot delay in extending flaps/gears would cause the aircraft to achieve the target speed below the target altitude, and, thus, must be taken into account by increasing the target altitude to a higher value. While reaching the target speed at a higher than desired target altitude would improve the probability that aircraft achieve the target speed (at the target altitude), it also means that the aircraft's thrust must be engaged early, which in turn increases the noise impact.

To resolve the tradeoff between target achievement and noise impact, a Monte Carlo simulation study was conducted with a fast-time B737-300 simulator. In the simulation, the altitude at which the thrust is reduced to idle and the target altitude for which the flap schedule is designed were varied to determine the best tradeoff between the probability of the aircraft achieving an altitude window of +/- 5 knots within the target speed, and the noise saving. Simulation results showed that: 1) the target altitude should be increased by 50 ft when there is no turbulence (the PF cues the PM to extend flaps); 2) the target altitude should be increased by 2000 ft and the thrust should be reduced at the TOD.

The impact of and mitigation strategies for the wind uncertainty were examined by analyzing the feasible space of the strategic control parameters. Three wind conditions, headwind, tailwind, and no wind, were used in the analysis. The headwind and tailwind, 30 knots at 10,000ft decreasing linearly to 10 knots at the surface, were used to present wind conditions that typically would be encountered in actual operation. Analysis results showed that the size of feasible space parameters (for flap schedule design) depends on wind uncertainty, and can be very small when the wind uncertainty is large. In such case, ANAAP implementation would be impractical, unless speed brake and thrust are used at the expense of increasing airframe and engine noise.

To support the implementation of strategic control parameters (H_{TOD}, $V_{TOD,}$ H_I, V_F, and H_F), two concepts for allocating the control function of these parameters between pilots and controllers were examined. Driven by the need for implementation in the near future, interviews with TRACON controllers were conducted, and it is recommended that the implementation should rely on the concept based on the distributed control allocation scheme, i.e., the controllers would use speed and altitude commands to setup the procedure parameters (H_{TOD}, $V_{TOD,}$ V_F, and H_F) while the pilots would perform the procedure by executing tasks such as reducing the thrust at H_I.

6.2. Development of a New Pilot Cueing System

Because the tactical control parameters implementation involves the use of the vertical navigation mode (VNAV) of the flight management system (FMS), the limitations of existing FMS VNAV logic along with the proposed solutions to overcome these limitations were reviewed. The review showed that the proposed solutions are highly automated and suggests a need for a simple, non-automated pilot cueing system that can be implemented in the near future. To explore this, the concept of using gates as a tactical control feedback mechanism was introduced. Each gate, consisting of an altitude and a speed, is essentially a checkpoint that can be placed along the descent for pilots to monitor aircraft deviation from the nominal speed profile and make adjustments to the nominal flap schedule based on the observed deviation. Gates cueing was investigated, and a prototype card was designed, in a simulator based, human factors experiment. Fifteen active airlines pilots participated in the experiment and flew continuous descent approaches. The principal results of the experiment showed that: 1) the target achievement improved approximately every two knots for the case when the pilot was not provided any information (no flap schedule or gates), to the case when the pilot was provided with a nominal flap schedule and no gate, to flap schedule with two gates, and to flap schedule with three gates; 2) in the presence of wind uncertainty, using gates, pilots were able to manage the deceleration and achieve the target altitude by observing the speed deviation at the gates and making the necessary adjustments to the nominal flap schedule; 3) pilots performed worst in the headwind condition (relative to no wind and tailwind). Given that most of the approaches are into a headwind, the gates can be beneficial in terms of avoiding thrust transients or level flights due to early target achievement because of the additional deceleration that accompanies a headwind.

The experiment results also provided many important insights into the issues concerning the human factors aspects of gates implementation, the design considerations of gates, and the integration of gates into the cockpit. First, the gates method was found to be intuitive for pilots and is well received by pilots in general. Second, the strategy which pilots used in the case when neither a nominal flap schedule nor gates were provided could be extremely valuable for training new pilots in how to use gates. Third, 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. Fourth, pilots' subjective feedback indicated that gates are very useful for managing the aircraft's deceleration and do not increase the workload if they are designed appropriately. Fifth, the format of the gates cueing card prototype was highly accepted by pilots.

6.3. Design Principle for Managing System Uncertainty

An outgrowth of this thesis is the design principle that rules can be designed as a mechanism that constrains a system's behavior into desirable form by providing specific, updated target states toward which the system should be controlled. To illustrate the utility of the principle, a random walk was used as a simple example to model the effect of growth in uncertainty and show the benefits of updating the target states. Another elaborate example of the VNAV procedure at Eagle, Co was also used to show that imposing procedures (i.e., flying dirty at approach speed with a detailed script) and updating the system with pilot crosscheck points (i.e., altitudes at specific distances) prove to be a viable concept for flying in a terrain-challenged environment. The application of the design principle to noise abatement approach procedures was demonstrated through the use of procedures to specify the order of thrust-reduction and pitch reduction at the top of descent. Finally, the design principle was also instrumental in the conceiving of the gates as a new pilot cueing system for implementation in the near future.

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Appendix A. Role of Procedures/Rules in Managing Uncertainty

The concept of using rules to manage uncertainty is a central part of this thesis and thus worthy of discussion. In Section A.1, the concept is formulated with the design principle that rules can be viewed as a mechanism that constrains behavior of a system into a desirable form by providing specific, updated target states toward which the system should be controlled. In Sections A.2 and A.3, a generic example (random walk) and an aviation example (VNAV 3 procedure at Eagle, Co) are used to illustrate the concept. In Section A.4, the application of the concept to noise abatement approach procedures is demonstrated through the use of procedures to specify the order of thrust-reduction and pitch reduction at the top of descent.

A.1. Rules as a Mechanism Enabling Desirable System Behavior

Rules are pervasive in our society. According to the Merriam-Webster dictionary, a rule is defined as

1 a : *a prescribed guide for conduct or action*
b : *the laws or regulations prescribed by the founder of a religious order for observance by its members*
c : *an accepted procedure, custom, or habit*
d** (1)* ***: *a usually written order or direction made by a court regulating court practice or the action of parties (2)* ***:*** *a legal precept or doctrine*
e : *a regulation or bylaw governing procedure or controlling conduct*

2 a** (1)* ***: *a usually valid generalization (2)* ***:*** *a generally prevailing quality, state, or mode*
b : *a standard of judgment*
c : *a regulating principle*
d : *a determinate method for performing a mathematical operation and obtaining a certain result*

These definitions resonate well with how rules are applied in a myriad of applications, ranging from computer programs that govern the operation of machines, to laws that govern human conduct, and to natural laws that regulate nature in particular and the universe in general. The implication and the underlying assumption deduced from these definitions is that rules are employed because they constrain behavior into a desirable form.

Although there are a wide range of rules and their applications, all rules are formulated by a synthesis of art and science, and can be grouped in five categories. For example, in a solution-based formulation, rules prescribe how things “should be”, as in civil codes, communications standards, or handbooks. On the other hands, in a method-based formulation, rules are synthesized based on mathematical or scientific principles. Examples of these rules include algorithms and procedures. Rules are also formulated by consensus, especially in complex systems where multiple stakeholders must be in agreement. Examples are civic laws (in a democratic society) or concurrent engineering. Relying on experience is also an important way to synthesize rules or procedures. These rules are based on common sense, and on heuristics, which are abstractions of lessons learned from experience.

In science and engineering, a prevalent type of rule is the standard operating procedure (SOP), which purports to provide guidance, usually through a series of sequential steps, for planning and implementing specific tasks in normal as well as contingency situations. For example, in aircraft operations, checklists are commonly used by pilots to help ensure that certain requirements are satisfied, such as the fully stabilized configuration requirement prior to landing. The fully stabilized configuration requirement allows the aircraft to consistently perform a successful landing by limiting the aircraft’s behavior, or by eliminating uncertainty such as having the gear un-extended at touchdown (which leads to a crash) or over-speeding above the aircraft’s approach speed prior to landing (which typically results in a go-around).

While a specific rule, such as an SOP, may not always provide the optimal solution for all operating conditions, systems operated by rules rely on them as a means to constrain behavior into a desirable form in an uncertain environment. In particular, rules constrain the behavior of a system in two ways:

1. as a mechanism that controls the state transition, which can happen continuously or discretely, so that the system state always remain in a predefined region. An abstraction

of this idea is illustrated in Figure 51, which shows that if the initial state of a system at time t_o is inside a predefined region bounded by rules, then the system shall remain inside this region for all future time t. In the context of control theory, an analogy of this predefined region is an invariant set. Specifically, a set G is an invariant set for a dynamic system if every system trajectory which starts from a point in G remains in G for all future time

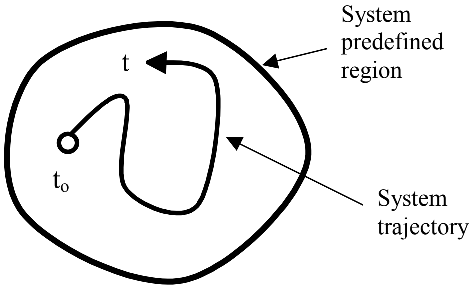


Figure 51: Abstraction of a Predefined Region Bounded By Rules

2. as a mechanism that drives the state back into the predefined region if the state is outside the predefined region as illustrated in Figure 52. An example is a circuit breaker.

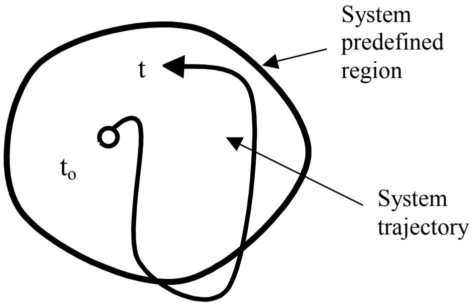


Figure 52: Rules Drive States Outside Predefined Region Back In.

Regardless of how rules are synthesized, they are advertently and succinctly written for usability, and often lead to apparently predictable, simple, and robust behavior. As a result, the underlying rationale that leads to the formulation of rules often can become hidden, causing users to apply rules without understanding the basis behind them. Despite this and the fact that solutions provided by rules can be sub-optimal, systems operated by rules rely on them as a means to constrain behavior into desirable outcomes in an uncertain environment. This "desirable-behavior constraint" feature is characteristic in systems that are operated by rules, and thus, motivates the design principle that: *"Rules can be designed as a mechanism that constrains a system's behavior into desirable form by providing specific, updated target states toward which the system should be controlled."*

Although it is not feasible to quantitatively express all the generalities of this design principle, two examples (random walk and RNAV procedure at Eagle, Co) are used to illustrate the consequences of imposing rules and show that when designed appropriately, rules constrain the system's behavior in an uncertain environment into desirable outcomes.

Before departing this Section, an important question associated with this design principle is how should rules be automated and allocated between humans and machines? Prior research [Karliardos 1999] has shown that for decision systems in which humans and machines interact, a feasible approach to address these questions is to use the Semi-Structured decision processes framework. This framework decomposes the processes in the system in question into Structured and Unstructured sub-processes. Structured processes are defined as those that can be reduced to well-defined rules, and Unstructured processes are those that cannot be reduced to well-defined rules. Using this framework, a designer can attempt to decompose and determine which processes are Structured and/or Unstructured, and then design the components appropriately. In this context, it is important to note that since automation consists of algorithms, which can be reduced to rules, automation is therefore a form of rule. For a detailed discussion of the Semi-Structured framework, the reader is referred to [Karliardos 1999].

A.2. A Generic Example: Random Walk

In systems that operate in the presence of disturbances (i.e., exogenous noise or perturbations) that are not accounted for in the design, the manifestation of the disturbances is that the uncertainty in the system's states can build up or grow with time. Without the imposition of rules (e.g., control laws or procedures), the uncertainty can drive the system range outside the design range[14]. In this section, a random walk is used as a simplified example to model this phenomenon, and to demonstrate the necessity of resetting or reinitializing the system states in order to keep the system range inside the design range.

Consider a one-dimensional random walk constructed as follows. At time t = 0, the system is initially at position $y = 0$. After each time-interval of length Δt, with equal probability the position is either incremented or decremented by an amount Δy. Then the state of the system at time t is given by

$$\Delta y \cdot (y[1] + y[2] + \cdots + y[\mathit{floor}(t/\Delta t)] \tag{1}$$

where the $\{y[k]\}_{k=1}^{k=\infty}$ are independent identically-distributed random variables, equal to ±1 with equal probability.

If $\Delta y = \sigma\sqrt{\Delta t}$ for a fixed parameter σ, and then in the continuous-time limit $\Delta t \to 0$, the random walk is the classical Brownian motion process or Weiner process [Ross 1997]. Denote the position due to this (continuous-time) random walk of the system at time t by $y(t)$. This limiting process can be characterized by its three defining properties:

1. $y(0) = 0$
2. The change $y(t) - y(s)$ over any interval $(s,t]$ is a random variable that depends only on the *length* $t - s$ of the interval, and is stochastically independent of the change over any non-overlapping interval(s).
3. At any time $t > 0, y(t)$ has a Gaussian distribution with mean 0 and variance $\sigma^2 t$.

---

[14] In design terminology, the design range is the error range that the system is designed for, and the system range is the actual error range observed in operation. The design goal is to keep the system range inside the design range.

It can be shown that the probability that $y(t)$ stays within a design range from $y = -\alpha$ to $y = \alpha$ decreases as the walk is progressed in time (or equivalently as the uncertainty builds up with time). The probability that $y(t)$ is outside the design range is given by

$$\begin{aligned} \Pr(|y(t)| > \alpha) &= 1 - \Pr(|y(t)| < \alpha) \\ &= 1 - \Pr(-\alpha < y(t) < \alpha) \\ &= 1 - 2erf\left(\frac{\alpha}{\sigma\sqrt{t}}\right) \end{aligned} \tag{2}$$

where erf denotes the error function $erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x ex(-t^2)dt$.

Obviously $erf(x)$ is an increasing function of x, hence $erf(1/\sqrt{t})$ is a decreasing function of t, and thus the probability that $y(t)$ is outside the design range $[-\alpha, \alpha]$ increases with time.

As a numerical example, a modified random walk is shown in Figure 53. Up to time T = 1, the random walk approximately simulates a Brownian motion process with σ = 1 and $\Delta t = 1e-5$. At time T, $y(t)$ is re-initialized to an arbitrary number inside the design range from $-\alpha$ to α. As shown in the figure, as the uncertainty grows up with time, the probability of staying outside the design range increases (or remaining inside the design range decreases). This means that a re-initialization is necessary to bring $y(t)$ back in the design range as illustrated with the re-initialization at T = 1.

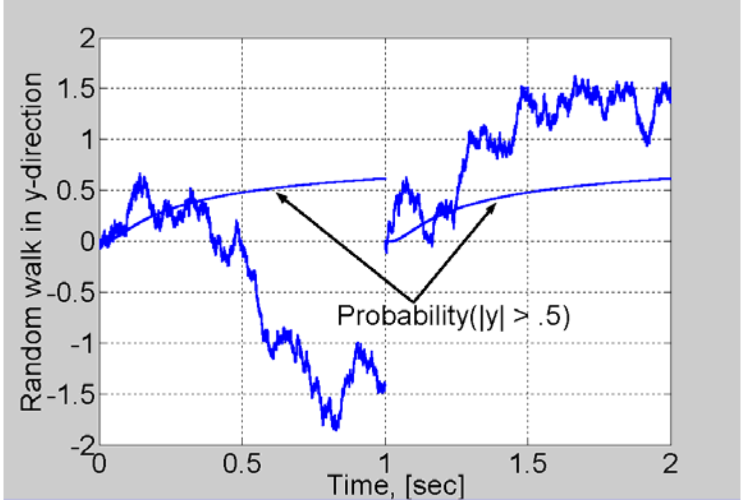


Figure 53: Random Walk with Random Step Sizes and a Fixed Time Step Size

This simple example reinforces the discussed design principle that the growth of uncertainty in a system can be managed by updated states for the walk. In the next section, this design principle will be illustrated on a more elaborate real-world example of the RNAV procedure at Eagle, Co, where the altitude checkpoints along the descent are designed to help the pilot detect altitude deviations and ensure that the aircraft remain within the vertical path design range by reinitializing the aircraft states as often as necessary.

A.3. An Aviation Example: KEGE Procedure

The American Airlines' arrival procedure into Eagle Colorado Airport (KEGE) is also a useful illustration of how procedures, embedded in pilot scripts and automation, can assist pilots performing landings in a difficult terrain environment.

A.3.1. Background

An aerial view of KEGE lying in a valley surrounded on three sides with mountains is shown in Figure 54. This mountainous geography earns KEGE the reputation as one of the most "terrain-challenged" airports in the US [Leib 2001]. There are three main requirements for day and night landing operations at KEGE. First, the aircraft must be safely kept away from the terrain.

Second, a controlled flight is executed throughout the approach so that the aircraft can timely and robustly respond to wind aloft. Third, there are adequate monitoring cues and contingency procedures for the pilots to perform an escape maneuver if at any time the aircraft state were projected to be unsafe.

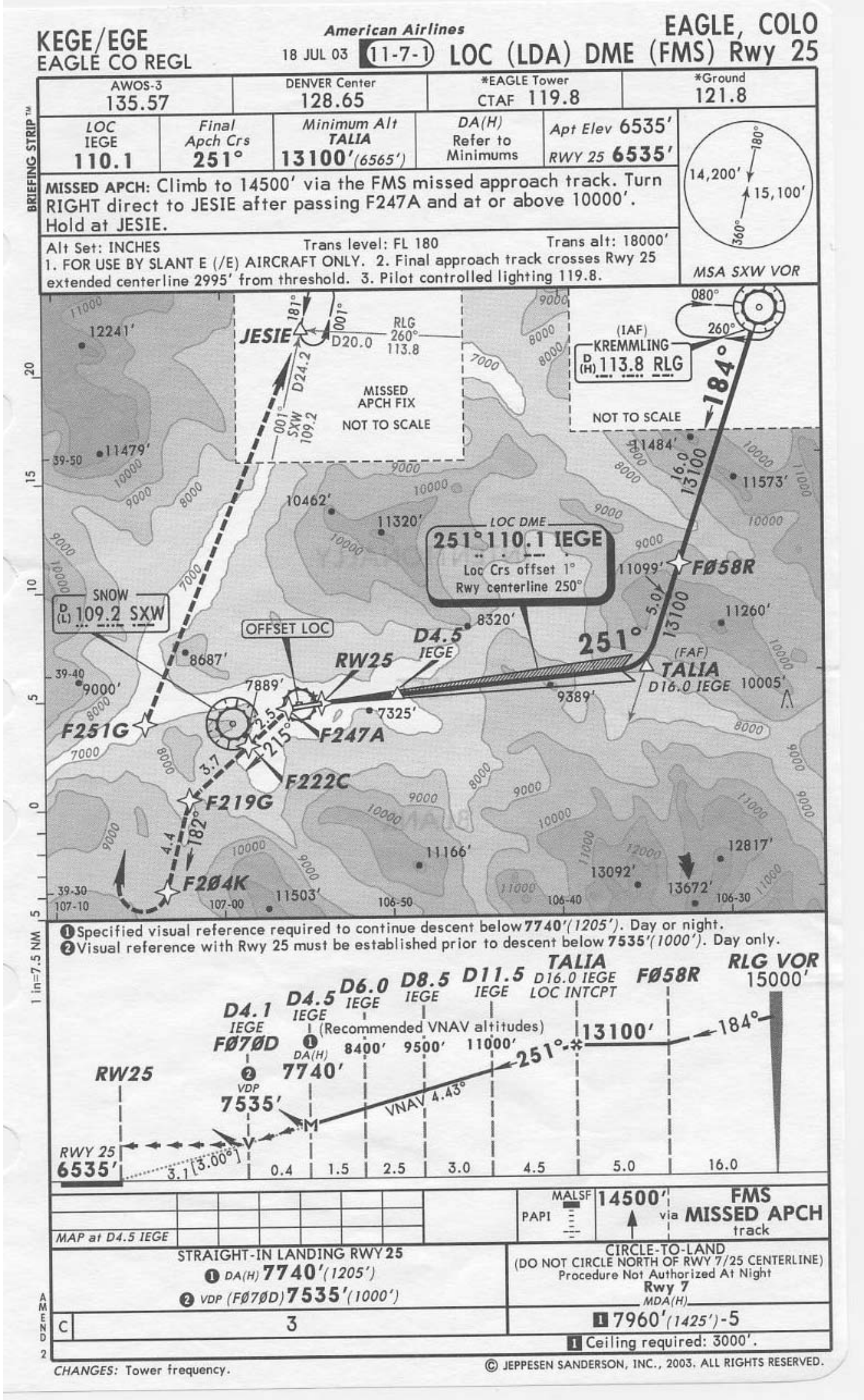
American Airlines has designed and operated a special procedure that satisfies these requirements. The operation of the procedure, described in the approach chart (Figure 55) and in the pilot procedure (Figure 56) below, involves the use of advance airborne guidance and navigation systems, an Area Navigation procedure, and a scripted pilot procedure. The detail of these systems and procedures are described in the next three sections.

Figure 54: Aerial View of KEGE

A.3.2. Guidance and Navigation System Requirements

The required guidance and navigation systems are the most advanced systems in the fleet of American Airlines. They are summarized in Figure 56, including: Inertial Reference Units, Flight Management System (FMC), an autopilot with heading (HDG) mode, altitude mode (ALT), vertical speed mode (V/S), localizer-capture mode (LOC), lateral navigation mode (LNAV), vertical navigation mode (VNAV), and Auto-throttle (A/T) in SPEED mode. The functions of these systems, coupled with the autopilot, can be categorized according to their usage in the lateral domain, vertical domain, or a combination thereof.

In combination, these modes allow the aircraft to fly either specific aircraft states (course, altitude, velocity) or a trajectory that is made of straight-line segments that are joined by waypoints. A waypoint, a point in the horizontal plane, is defined by a longitude and a latitude. Guidance and navigation that utilize waypoints with constraints (speed, altitude, and course) at these waypoints are referred to as Area Navigation (RNAV).



KEGE/EGE
EAGLE CO REGL

American Airlines
18 JUL 03 (11-7-1) **LOC (LDA) DME (FMS) Rwy 25**

EAGLE, COLO

AWOS-3	DENVER Center	*EAGLE Tower	*Ground
135.57	128.65	CTAF 119.8	121.8

LOC	Final Apch Crs	Minimum Alt	DA(H)	
IEGE 110.1	251°	TALIA 13100′(6565′)	Refer to Minimums	Apt Elev 6535′ RWY 25 6535′

MISSED APCH: Climb to 14500′ via the FMS missed approach track. Turn RIGHT direct to JESIE after passing F247A and at or above 10000′. Hold at JESIE.

Alt Set: INCHES Trans level: FL 180 Trans alt: 18000′
1. FOR USE BY SLANT E (/E) AIRCRAFT ONLY. 2. Final approach track crosses Rwy 25 extended centerline 2995′ from threshold. 3. Pilot controlled lighting 119.8.

14,200′ 180° 15,100′ 360°
MSA SXW VOR

①Specified visual reference required to continue descent below 7740′(1205′). Day or night.
②Visual reference with Rwy 25 must be established prior to descent below 7535′(1000′). Day only.

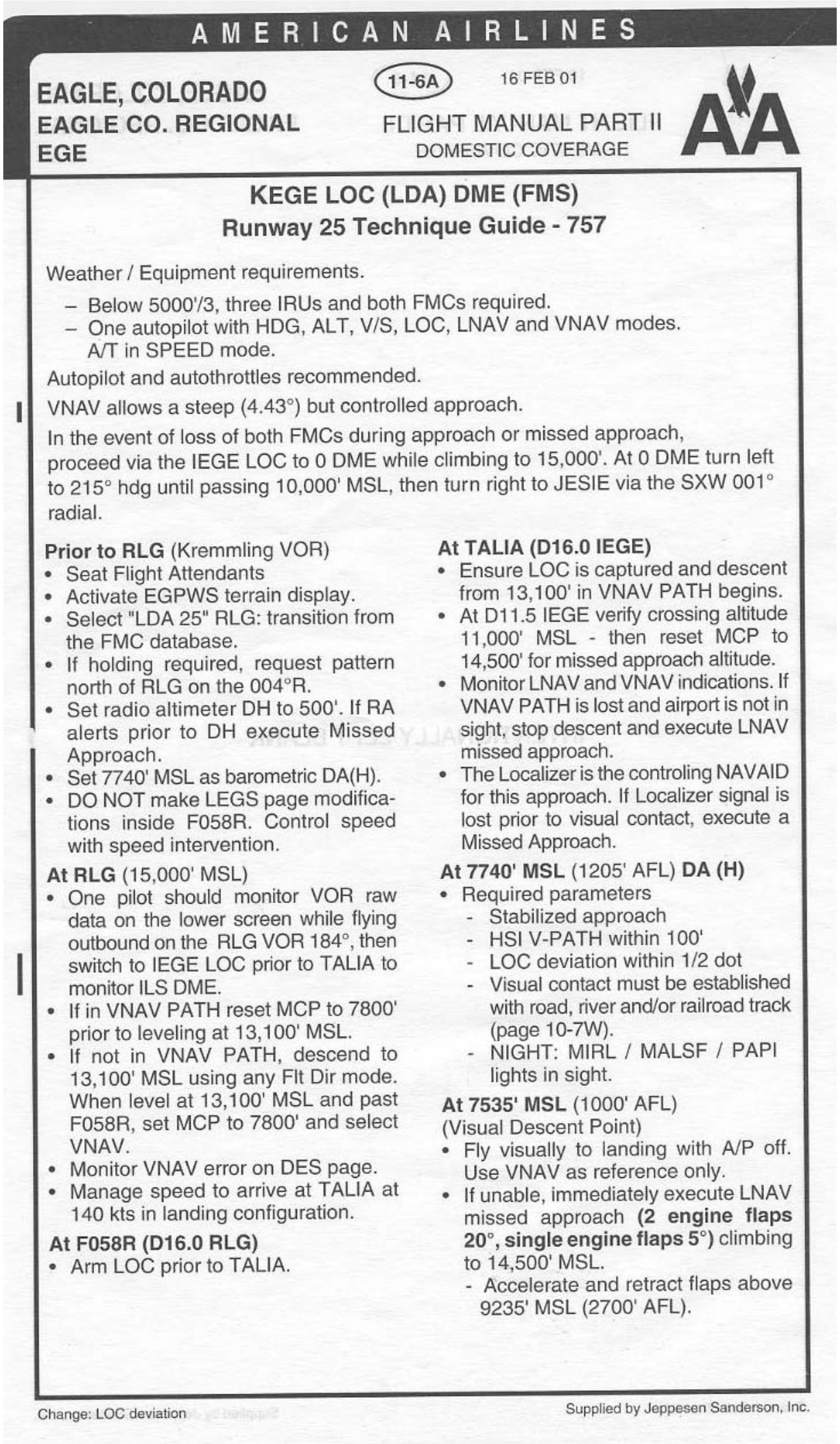
MAP at D4.5 IEGE

14500′ via FMS MISSED APCH track

STRAIGHT-IN LANDING RWY 25	CIRCLE-TO-LAND (DO NOT CIRCLE NORTH OF RWY 7/25 CENTERLINE) Procedure Not Authorized At Night Rwy 7 MDA(H)
① DA(H) 7740′(1205′) ② VDP (F070D) 7535′(1000′)	
C 3	① 7960′(1425′)-5
	① Ceiling required: 3000′.

CHANGES: Tower frequency.

Figure 55: KEGE Approach Chart [Reproduced with permission of American Airlines and Jeppesen Sanderson, Inc. Not to be used for navigation.]



AMERICAN AIRLINES

EAGLE, COLORADO
EAGLE CO. REGIONAL
EGE

11-6A 16 FEB 01

FLIGHT MANUAL PART II
DOMESTIC COVERAGE

KEGE LOC (LDA) DME (FMS)
Runway 25 Technique Guide - 757

Weather / Equipment requirements.

- Below 5000'/3, three IRUs and both FMCs required.
- One autopilot with HDG, ALT, V/S, LOC, LNAV and VNAV modes. A/T in SPEED mode.

Autopilot and autothrottles recommended.

VNAV allows a steep (4.43°) but controlled approach.

In the event of loss of both FMCs during approach or missed approach, proceed via the IEGE LOC to 0 DME while climbing to 15,000'. At 0 DME turn left to 215° hdg until passing 10,000' MSL, then turn right to JESIE via the SXW 001° radial.

Prior to RLG (Kremmling VOR)
- Seat Flight Attendants
- Activate EGPWS terrain display.
- Select "LDA 25" RLG: transition from the FMC database.
- If holding required, request pattern north of RLG on the 004°R.
- Set radio altimeter DH to 500'. If RA alerts prior to DH execute Missed Approach.
- Set 7740' MSL as barometric DA(H).
- DO NOT make LEGS page modifications inside F058R. Control speed with speed intervention.

At RLG (15,000' MSL)
- One pilot should monitor VOR raw data on the lower screen while flying outbound on the RLG VOR 184°, then switch to IEGE LOC prior to TALIA to monitor ILS DME.
- If in VNAV PATH reset MCP to 7800' prior to leveling at 13,100' MSL.
- If not in VNAV PATH, descend to 13,100' MSL using any Flt Dir mode. When level at 13,100' MSL and past F058R, set MCP to 7800' and select VNAV.
- Monitor VNAV error on DES page.
- Manage speed to arrive at TALIA at 140 kts in landing configuration.

At F058R (D16.0 RLG)
- Arm LOC prior to TALIA.

At TALIA (D16.0 IEGE)
- Ensure LOC is captured and descent from 13,100' in VNAV PATH begins.
- At D11.5 IEGE verify crossing altitude 11,000' MSL - then reset MCP to 14,500' for missed approach altitude.
- Monitor LNAV and VNAV indications. If VNAV PATH is lost and airport is not in sight, stop descent and execute LNAV missed approach.
- The Localizer is the controling NAVAID for this approach. If Localizer signal is lost prior to visual contact, execute a Missed Approach.

At 7740' MSL (1205' AFL) **DA (H)**
- Required parameters
  - Stabilized approach
  - HSI V-PATH within 100'
  - LOC deviation within 1/2 dot
  - Visual contact must be established with road, river and/or railroad track (page 10-7W).
  - NIGHT: MIRL / MALSF / PAPI lights in sight.

At 7535' MSL (1000' AFL)
(Visual Descent Point)
- Fly visually to landing with A/P off. Use VNAV as reference only.
- If unable, immediately execute LNAV missed approach **(2 engine flaps 20°, single engine flaps 5°)** climbing to 14,500' MSL.
  - Accelerate and retract flaps above 9235' MSL (2700' AFL).

Change: LOC deviation

Supplied by Jeppesen Sanderson, Inc.

Figure 56: Pilot Procedure [Reproduced With Permission of American Airlines and Jeppesen Sanderson, Inc. Not to be used for navigation.]

In the lateral domain, the FMS manages the aircraft's control functions in a number of modes. In LNAV mode, the aircraft follows a lateral ground track defined by the connection of a series of waypoints. In the HDG Mode, the FMS performs control actions required to achieve a selected heading. The LOC Mode captures the localizer signal and provides the lateral guidance during the approach.

A number of similar modes exist in the vertical domain. In the VNAV mode, the FMS plans and executes a vertical path and a speed profile based on altitude and speed constraints at the waypoints that make up the speed and altitude trajectory. The other modes include: (1) the V/S mode, which allows the aircraft to climb or descend at a selected vertical speed.; (2) the Flight Level Change Mode (FLCH), which allows the aircraft to climb or descend at a fixed thrust and a fixed airspeed; and (3) the ALT mode, which allows the aircraft to maintain a specified altitude.

A.3.3. RNAV Procedure

The procedure that pilots use to fly into KEGE is a RNAV procedure. Table 5 lists the waypoints along with their corresponding speed, altitude, and course constraints. As shown in the table, the aircraft enters the TRACON at RLG with a speed of 250 knots and an altitude of 15000 ft. The aircraft next descends to 13100 ft by the time it reaches F058R. Thereafter, the aircraft maintains its altitude at 13100 ft and reduces its speed to 140 knots at TALIA. From TALIA to touchdown, the aircraft maintains its speed at 140 knots while descending.

The pages from the flight manual that describes the procedure pilots are mandated to review prior to flying into KEGE are shown in Figure 55 and Figure 56. A number of key elements distinguish this approach from a typical ILS approach. Foremost among these is that the navigation and guidance system is comprised of the localizer, the distance measurement equipment (DME), and the FMS, rather than the standard set an ILS's avionics equipment, which include the localizer, the glide slope, and marker beacons. This unique combination allows the aircraft to use VNAV mode to track a non-standard glide slope angle of 4.43 degrees. This high glide slope angle, designed to increase the aircraft separation from the terrain, translates into a requirement that the aircraft captures the virtual three-degree glide path (the glide slope transmitter is not available) from above at DME 4.1. Because there is an offset between the localizer and the virtual three-degree glide path, the pilots have to use visual cues to acquire the virtual three-degree glide path and manually fly the aircraft thereafter. Night arrivals must use this LOC/DME/FMS approach combination, and no other approaches are authorized.

Waypoint	**Speed Constraint**	**Altitude Constraint**	**Course Constraint**
RLG	250 knots	15000 ft	186 deg
F058R		13100 ft	184 deg
TALIA	140 knots	13100 ft	251 deg
F070D	140 knots	7540 ft	251 deg
RW25	140 knots	6590 ft	

Table 5: Speed, Altitude, and Course Constraints

Other important features of this procedure include the recommendation for the aircraft to meet specific altitudes at fixed DME distances and a scripted pilot technique guide that provides instructions at each waypoint. The details of these elements and the rationale for their usage are discussed in the next section.

A.3.4. Pilot Technique-Guide Script

Below is the pilot technique-guide script, listed and discussed chronologically, starting from the time the aircraft first enters the TRACON until the aircraft reaches the runway threshold.

Prior to RLG (Kremmling VHF Ominidirectional Range (VOR))

- *Activate EGPWS terrain display*

- *Select "LDA (localizer directional aid) 25"*
- *If holding required, request pattern north of RLG on the 004°R*
- *Set radio altimeter DH to 500'.*
- *If RA (radio altimeter) alerts prior to DH execute Missed Approach*
- *Set 7740ft mean sea level (MSL) as barometric DA(H)*
- *Do not make LEGS page modifications inside F058R*
- *Control speed with speed intervention.*

Discussion: Pilots activate alert and collision avoidance systems to obtain visual terrain information for terrain awareness. As advised, a missed approach is executed if the RA alerts prior to DH. In addition, to maintain situation awareness, pilots are also advised to refrain making LEGS page modification because doing so would increase head-down time and one pilot may be unaware of the changes that another pilot makes. The advice to control speed with speed intervention enables the pilots to make speed adjustments using the MCP and keep the aircraft in VNAV PATH mode. This advice is very important because VNAV, under certain conditions in the interaction with the auto-throttle, may switch VNAV PATH mode to VNAV SPD mode, which may result in undesirable consequences. For example, a stronger than predicted headwind would cause the auto-throttle to supply an excessive amount of thrust to maintain speed (since the auto-throttle logic may lag). To arrest the acceleration cause by the excessive thrust, VNAV would shallow out the flight path angle to slow down the aircraft, and consequently take the aircraft off the desired vertical path. The reader is preferred to section 3.4.2.2 for more examples.

At RLG (15,000' MSL)

- *One pilot should monitor VOR raw data on the lower screen while flying outbound on the RLG VOR 184°, then switch to IEGE LOC prior to TALIA to monitor ILS DME*

- *If in VNAV PATH, reset MCP to 7800' prior to leveling at 13,100' MSL.*
- *If not in VNAV PATH, descend to 13,100' MSL using any Flt Dir Mode (FLCH OR V/S). When level at 13,100' MSL and past F058R, reset MCP to 7800' and select VNAV*

- *Monitor VNAV error on DES Page.*
- *Manage speed to arrive at TALIA at 140 knots*

Discussion: Starting from RLG, one pilot is required to monitor the aircraft position deviation using VOR raw data and the LOC DME. It is important to check FMC position against raw data because of the update provided by navigation aids may be inaccurate. To help the pilots adhere to the planned vertical path and to monitor the descent progress, instructions are provided to ensure that VNAV PATH mode is engaged at F058R. The advice to manage speed to arrive TALIA at 140 knots has several important implications. First, it prepares the aircraft to be in a stabilized, landing configuration. This is critical because malfunctions in the control systems, such as overshooting or undershooting the localizer due to late or early turning, have less damaging consequences at low speeds than at high speeds. Second, since the flight path angle of 4.43 degrees until to DME 4.1 is relatively high, flying at low speed gives pilots more time to check, from DME 4.1 to the runway, whether the aircraft is on the virtual three-degree glide slope by comparing altitudes with distances from the runway's threshold[15].

At F058R (D16.0 RLG)

- *Arm LOC prior to TALIA*

Discussion: Engaging the aircraft in the LOC mode locks the aircraft in lateral guidance provided by the localizer. Typically, the LOC mode is engaged during the final approach segment where the aircraft is about three or four miles from the runway or four miles from the extended runway centerline. In this procedure, the initiation of LOC mode at D16 starts the aircraft in the final approach segment early because the aircraft is most stabilized and least sensitive to disturbances in the final approach segment.

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[15] In an approach without the glide slope transmitter, a rule of thumb that pilots use to ensure that the aircraft is approximately along the three-degree glide slope is to multiply the altitude by 3/1000 to get the distance from the runway and then compare this distance with the reading from the DME. For example, 1000 ft approximately corresponds to 3NM from runway.

At TALIA(D16.0 IEGE)

- *Ensure LOC is captured and descent from 13,100' in VNAV Path begins.*
- *At D11.5 IEGE verify crossing altitude 11,000' MSL – then reset MCP to 14,500' for missed approach altitude.*
- *Monitor LNAV and VNAV indications. If VNAV PATH is lost and airport is not in sight, stop descent and execute LNAV missed approach.*
- *The Localizer is the controlling NAVAID for this approach. If Localizer signal is lost prior to visual contact, execute a Missed Approach.*

Discussion: Once control of the aircraft is based on the FMS navigation, the pilots are required to verify crossing altitudes at specific distances. The verification is used to detect trends in altitude deviations. The instructions also provide criteria for escape maneuvers if VNAV PATH or localizer signal is compromised.

At 7740' MSL (1205' AFL) DA(H)

Requirement parameters: Stabilized approach, HSI V-PATH within 100 (this is the tolerance) first point to break out, LOC deviation within ½ dot, visual contact must be established with road, river and/or railroad track, NIGH: MIRL(Medium intensity runway lighting)/MALSF(medium-intensity approach lighting system with RAIL/PAPI(precision approach path indicator) lights in sight

Discussion: Pilots are instructed to ascertain that requirement parameters are met in order to proceed with the landing. These parameters are typical in a visual approach procedure.

At 7535' MSL (1000' AFL)

- *(Visual Descent Point) Fly visually to landing with A/P off. Use VNAV as reference only.*

- *If unable, immediately execute LNAV missed approach (2 engine flaps 20^o, single engine flaps 5^o) climbing to 14500' MSL. Accelerate and retract flaps above 9235' MSL (2700' AFL).*

Discussion: Because of technical limitations of the auto-flight system and the presence of an offset localizer, the aircraft has to be flown manually and VNAV is used as a reference.

A.3.5. Discussion

The description of the procedure's parameters (guidance and navigation requirements, RNAV procedure, pilot procedure) and their rationale for their design described in the previous three sections suggest that the terrain-challenged day or night landing operations at KEGE are managed by: (1) constraining the behavior of the aircraft with stabilized configuration requirements; (2) using automation and navigation aids to ensure that the aircraft follow prescribed trajectory and meet hard navigation constraints with acceptable deviation; (3) providing feedback mechanisms to update the target states that the pilot is attempting to follow.

As specified in the RNAV procedure, the aircraft turns onto the final approach course at TALIA at a speed of 140 knots. Depending on the weight of the aircraft and the landing flap set by the pilots, this speed is either the landing speed or a few knots above the landing speed. In either case, an aircraft that flies at 140 knots must have high flaps, twenty-five or thirty degrees for adequate stall margin, and landing gear extended to preclude the audible configuration warning. Flying at or near the landing flap setting and with gear extended, also known as flying "dirty", puts the aircraft in a stabilized configuration throughout the descent and ensures that adequate drag is available to prevent the aircraft from accelerating along the steep 4.43 degrees glide path. Thus, this method of flying dirty at a slow speed is an effective way to limit the behavior of the aircraft into a desirable from.

Limiting aircraft behavior into desirable form with stabilization requirements is only meaningful if the aircraft is capable of meeting altitude targets and tracking the prescribed trajectory with acceptable deviation. In this approach, dictated by the proximity of the mountains and the offset of the localizer, the vertical path of the trajectory commands an unconventional glide slope of 4.43 degrees. For accurate navigation, the FMS was used in conjunction with navigation aids (LOC and DME) to minimize any deviation in the vertical and horizontal paths that might have occurred if the plane were flown conventionally. As illustrated in the approach plate, the FMS manages vertical and horizontal navigation, and reduces pilots' task to that of monitoring the aircraft states until the aircraft reaches the decision height at DME 4.5 with the following requirements met: stabilized approach configuration, HIS V-PATH within 100 feet, LOC deviation within ½ dot, and visual contact with the ground. These requirements help the pilots smoothly capture and transition to virtual three-degree glide slope and that the ensuing behavior of the aircraft is a controlled approach with a high margin safety. Thereafter, the pilots can visually fly along the virtual three-degree glide path manually with VNAV as a reference. This is a standard procedure that pilots can execute with high precision.

Finally, the recommended VNAV altitudes at different DME distances serve as a feedback mechanism that provide updates of the aircraft's desired vertical path and helps the pilot track the desired vertical profile. In particular, each time the aircraft crosses any of the DME distances specified in the approach chart, the pilot determines the deviation of the aircraft's altitude from the recommended VNAV altitude. This observed deviation helps the pilot detect any trends in altitude deviation and perform corrective actions if an unacceptable altitude deviation occurs. By repeating this process as the aircraft successively crosses the VNAV recommended altitudes, the pilot can ensure that the aircraft would not deviate too far from the desired profile throughout its progress to the decision altitude. It is also important to note that the closer the recommended VNAV altitudes are to the runway, the closer they are placed from each other. This increase in the placement of the recommended altitudes provides essential updates of altitude deviation that are an important part of the criteria that the pilot uses, at the decision height (D4.5) and at the visual descent point (D4.1), to decide whether to land or perform a missed approach. The hard constraints at the decision altitude and the visual descent point, thus, can be used as feedback references, although failing to meet the required parameters of these constraint results in a missed approach.

A.4. Application of rules for ANAAP

The last two examples demonstrated that rules enable desirable behavior in uncertain environments. In this section, this concept is applied to the problem of managing the order of thrust-reduction and pitch-reduction at the TOD in ANAAPs so that the impact on throughput is minimized.

An important source of uncertainty that affects the performance of ANAAPs is the order in which the thrust and pitch is reduced at the TOD. Eight different ANAAPs speed profiles of a B747-400, flown by eight airline pilots in a full motion flight simulator, are shown in Figure 57. While all the profiles' speeds prior to the interception of glide slope were at the instructed speed of 250 knots, the speeds immediately after glide slope interception varied by 5 knots. This variability was the result of the order in which the pitch and thrust were reduced. Specifically, if the aircraft pitch was reduced before the thrust was reduced to idle, the speed immediately after intercepting the glide slope was higher than 250 knots due the sudden partial loss of lift. Conversely, if the thrust was reduced to idle before the aircraft pitch was reduced, the speed is slower than 250 knots immediately after the glide slope was intercepted. This variability would influence the trajectory of the aircraft, and consequently, the separation between aircraft performing ANAAP.

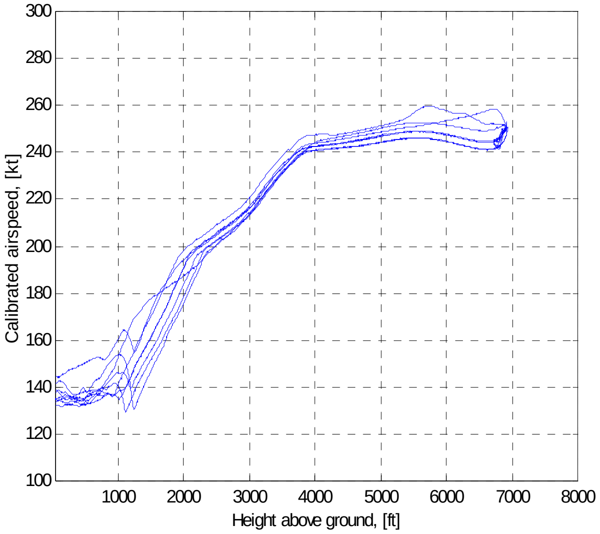

Figure 57: Speed Profiles of ANAAPs with Random Order of Speed and Thrust Reduction.

To demonstrate this, Monte Carlo simulation studies were performed with two aircraft simulators, a B737 leading a B747, as shown in Figure 58. The aircraft were assumed to fly initially at a constant altitude of 7000 feet at 250 knots, and upon intercepting the glide slope where the procedure commences, the aircraft followed a predetermined flap schedule with their thrust set to idle as depicted in Figure 58. The details of the aircraft simulators' dynamics are described in Appendix B. The aircraft control functions were performed by autopilot and navigation control logic while the pilot response times were assumed to follow a normal distribution with a mean of 2.8 seconds and a standard deviation of 2.2 seconds. The speed flap schedule and initial altitude were specified at the beginning of the procedure and remained fixed thereafter. A position uncertainty of 150 m, a typical resolution of airport surveillance radars, was also added at the start of the procedure. Since the engines were at idle throughout most of the descent, the flap was used as the main drag device that reduced the speed. The speed flap schedule was designed to keep the aircraft as clean as possible to minimize the drag, which in turn reduced airframe noise. Upon reaching the approach speed, the thrust was increased to maintain this speed. In addition, the order in which the aircraft reduced thrust and pitch at the TOD (where the aircraft intercepted the glide slope) was chosen randomly to emulate the speed variation phenomenon observed in Figure 57, and an initial separation of nine nm was used to ensure that the required minimum Instrument Flight Rule [Anon 2001] wake vortex separation (three nautical miles in the terminal area and 2.5 nautical miles in the final approach) was maintained throughout the procedure.

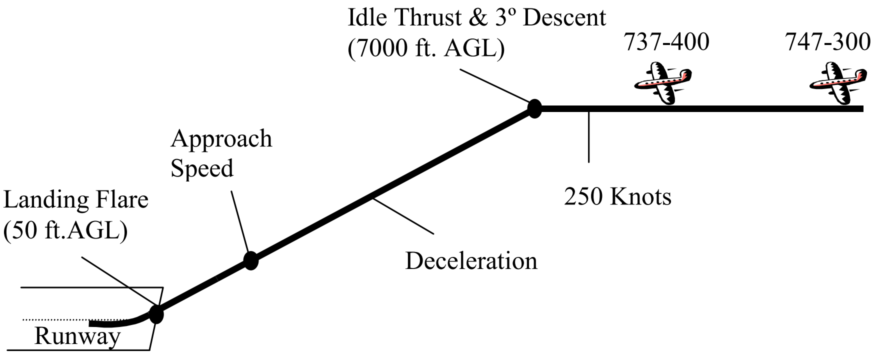

Figure 58: A B737-300 Leading a B747-400 Performing ANAAP

The simulation was run (approximately 300 times) until the results converged, and the probability density function (PDF) of the separation between the two aircraft when the B737 reached the threshold is shown in Figure 59. As shown, the PDF has three peaks at approximately 2.7, 3.2, and 3.7 nm of separation at the threshold. The three peaks are a result of the randomness in the order in which the aircraft thrust and pitch were reduced. For instance, if the B737's pitch was reduced before its thrust was reduced and the B747's thrust was reduced before its pitch was reduced, then immediately after intercepting the glide slope the speed of the B737 would be slightly faster than 250 knots and the B747 slower than 250 knots, resulting in a greater separation than expected. Hence the final separation is 3.7 nm. However, if both aircraft reduced pitch and thrust in same order, then the resulting separation was about 3.2 nm. For the case when the B737's thrust was reduced before it pitch was reduced and B747's pitch was reduced before its thrust was reduced, then the resulting separation was approximately 2.7 nm. The PDF of the separation when the simulation was run for this case alone is shown in Figure 60.

Since the throughput of a runway increases as the separation between aircraft decreases, it would be beneficial to introduce a procedure that specifies the order in which the aircraft reduces thrust and pitch. In this particular case, for an approach speed of 140 knots, an average separation of 2.7 nm would translate into a runway capacity of 52 aircraft per hour, whereas an average separation of 3.7 nm would translate into only 30 aircraft per hour.

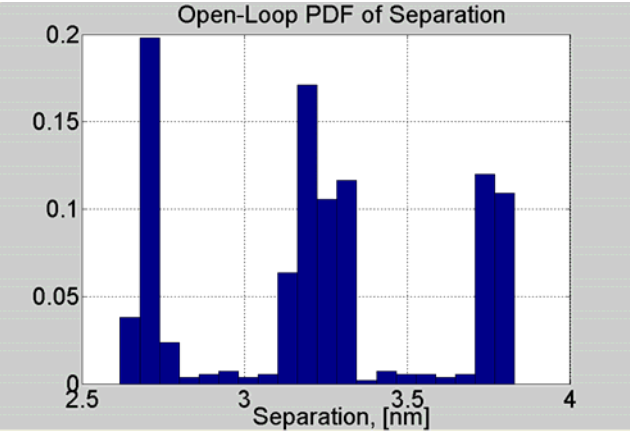

Figure 59: PDF of Aircraft Separation with Random Order of Pitch and Thrust Reduction

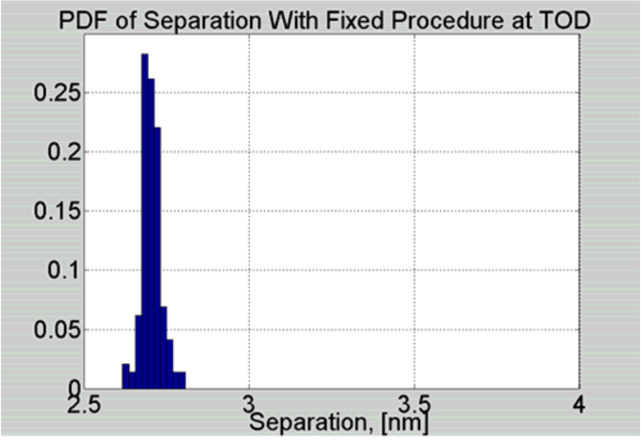

Figure 60: PDF of Aircraft Separation with Fixed Order of Pitch and Thrust Reduction

Appendix B. B737-300/B747-400 Simulator

To support Monte Carlo simulation studies, a fast time simulator was developed in Matlab. The dynamics of the simulators is based on a single-point-mass model [Kuchar 1999] with the following assumptions: 1) Aircraft behaves as a point mass (no rotation, inertia); 2) No slide-slip $\{\beta = 0, v = 0\}$, coordinated turn; 3) Thrust is along the body axis; 4) Controls pilot has go directly to applied forces; 5) Other body rates (q & r) are determined by the curvature of the trajectory (i.e., cannot pitch without climbing).

The simulation loop is shown in Figure 61, where, respectively, N, E, D denote the positions in the earth-reference coordinate; u, v, and w denote the velocities along the x, y, z axes in the aircraft body coordinate; p, q, and r, denote pitch, roll, and yaw rates; θ, ψ, φ are the pitch, roll, and yaw Euler-orientation angles; β and α denote the side slip angle and angle of attack; δ, ρ, AR, and C_D denote the control input, the density, the aspect ratio, and the drag coefficient; X and Z denote the body-axis forces; L, D, T, m, and g denote the lift, drag, thrust, mass, and gravitational constant; and the C's are the coordinate transformation matrices.

The aerodynamic model was programmed to be modular so that any aircraft could be simulated if its aerodynamic model is available. For the simulation work presented in the body of this thesis, the Boeing proprietary aerodynamic models and thrust performance data of the B737-300, B757-200, and B747-400 were used.

The aircraft control functions were performed by autopilot and navigation control logic, which execute aircraft modes such as level flight, level turn, climb/airspeed hold, and three-degree slope angle hold. The simulator's input includes the flap schedule, initial aircraft states, wind or disturbances models, pilot response model, and position uncertainty of airport surveillance radar (ASR). In addition to being used as a tool to determine the probability of separation violation and capacity impact of ANAAP, the simulators were also used to evaluate the aircraft's deceleration performance and maneuverability.

Because the fidelity of the aircraft deceleration performance was paramount for procedure design, the performance of the simulator aircraft flying both noise abatement approaches and standard ILS approaches was compared with that of the NASA Ames Full-motion B747-400 simulator, which is certified for pilot training and research. The comparison showed that the trajectory and other aircraft states of the simulated aircraft closely follow those of the NASA simulator, and, thus, validated the simulator for the research purpose in this thesis.

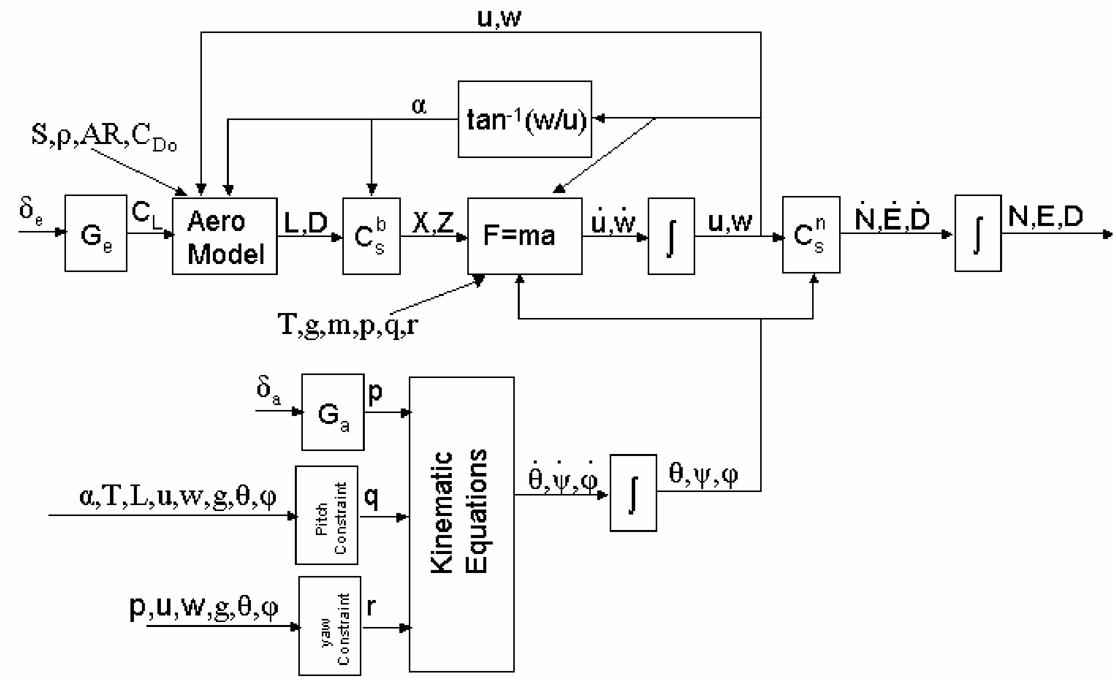

Figure 61: Point-mass Simulation Loop [Kuchar 1999]

Appendix C. Experiment Data

C.1. ANOVA Results

The statistical software package SPSS 10.0 for Windows was used to perform ANOVA and other related tests.

C.1.1. Validation of ANOVA Assumptions

Test of Sphericity (Mauchly’s test):

An important assumption made in the ANOVA is the assumption that the variances of the differences between treatment levels are the same. This assumption, known as the assumption of sphericity, is analogous to the assumption of homogeneity of variance in between-subject ANOVA. Mauchly’s test, which tests the hypothesis that the variances of the differences between conditions are equal, is usually used to check this assumption. If Mauchly’s test statistics is not significant (Sig. > .05), then it is reasonable to conclude that the variances of the differences are not significantly different. On the other hand, if Mauchly’s test statistic is significant (Sig. < .05), then the condition of sphericity is not met, and other statistical estimates, such as the Greenhouse-Geisser estimates and Huynh-Feldt estimates, can be applied the correct the degrees of freedom used to calculate the F-ratio. Table 6 shows the results of Mauchly’s sphericity test for the two main effects (of feedback mechanism and wind) and one interaction effect of the two main factors. The significance values of these tests indicate that all three effects meet the assumption of sphericity.

					Epsilon[a]		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse-Geisser	Huynh-Feldt	Lower-bound
WIND	.769	1.050	2	.592	.812	1.000	.500
FM	.455	2.931	5	.719	.737	1.000	.333
WIND * FM	.000	.	20	.	.422	.891	.167

Table 6: Mauchly’s Test of Sphericity

Test of Normality (Kolmogorov-Smirnov test):

The ANOVA also assumes that the data come from a normally distributed population. The Kolmogorov-Smirnov test, which compares the set of scores in the sample to a normally distributed set of scores with the same mean and standard deviation, is typically used to test this assumption. If the test is non-significant (Sig. > 0.05), then the distribution of the sample is not significantly different from a normal distribution. On the other hand, if the test if significant (Sig. < 0.05), then the sample distribution is significantly different from a normal distribution. Table 7 shows the results of the Kolmogorov-Smirnov test. The significance values indicate that the data come from a normally distributed population.

Experimental Conditions	**Kolmogorov-Smirnov**		
	Statistic	**df**	**Significance**
NFS-0G-NW	0.286	6	0.136
NFS-0G-TW	0.222	6	0.2
NFS-0G-HW	0.158	6	0.2
FS-0G-NW	0.21	6	0.2
FS-0G-TW	0.289	6	0.129
FS-0G-HW	0.262	6	0.2
FS-2G-NW	0.279	6	0.157
FS-2G-TW	0.194	6	0.2
FS-2G-HW	0.265	6	0.2
FS-3G-NW	0.352	6	0.019
FS-3G-TW	0.226	6	0.2
FS-3G-HW	0.232	6	0.2

Table 7: Kolmogorov-Smirnov Test of Normality

C.1.2. A Sample ANOVA Table

Tests of Within-Subjects Contrasts: NW and NFS as Base Categories

Source	WIND	FM	Type III Sum of Squares	df	Mean Square	F	Sig.
WIND	HW vs. NW		238.39	1	238.39	21.57	0.00
	TW vs. NW		31.00	1	31.00	2.04	0.18
Error(WIND)	HW vs. NW		154.71	14	11.05		
	TW vs. NW		213.21	14	15.23		
FM		FS-0G vs. NFS	92.28	1	92.28	10.48	0.01
		FS-2G vs. NFS	356.29	1	356.29	79.69	0.00
		FS-3G vs. NFS	732.53	1	732.53	138.07	0.00
Error(FM)		FS-0G vs. NFS	123.27	14	8.80		
		FS-2G vs. NFS	62.60	14	4.47		
		FS-3G vs. NFS	74.28	14	5.31		
WIND * FM	HW vs. NW	FS-0G vs. NFS	94.12	1	94.12	0.85	0.37
		FS-2G vs. NFS	13.14	1	13.14	0.18	0.68
		FS-3G vs. NFS	208.77	1	208.77	3.37	0.09
	TW vs. NW	FS-0G vs. NFS	13.80	1	13.80	0.35	0.56
		FS-2G vs. NFS	17.34	1	17.34	0.40	0.54
		FS-3G vs. NFS	0.42	1	0.42	0.01	0.92
Error(WIND*FM)	HW vs. NW	FS-0G vs. NFS	1543.20	14	110.23		
		FS-2G vs. NFS	1048.49	14	74.89		
		FS-3G vs. NFS	866.47	14	61.89		
	TW vs. NW	FS-0G vs. NFS	555.86	14	39.70		
		FS-2G vs. NFS	602.61	14	43.04		
		FS-3G vs. NFS	609.67	14	43.55		

C.2. Questionnaires

SUBJECT INFORMATION

The purpose of this study is to design and evaluate a pilot cueing system for noise abatement approach procedures. All your information and answers will be confidential and anonymous. Your participation is voluntary. You may decline to answer any or all questions. You may decline further participation, at any time, without adverse consequences.

Subject Number:____________________________ Date: __________

Age___________

Current in what type aircraft? _________________________

Date of last flight? _________________________

Experience with noise abatement approach procedures?
____

Experience with any arrival procedure energy management guidance tools? _________________

Pilot License (check all applicable): ○ Commercial ○ Private ○ Airline Transport ○ Student Pilot

Level of training (check all applicable): ○ Instrument Rating ○ Aerobatics Rating ○ Multi-Engine Rating
○ Multi Crew Training (e.g., CCC, MCC) ○ Flight Instructor (Initial Flight Training, e.g., CFI)
○ Type Rating Instructor (if yes, name types:_______________________)
○ Type Rating Examiner (if yes, name types:_______________________)

Please list you flight experience

	Type	Total	Total Instrument	Total Last 12 month	Total Last 6 month	Inst. Appr. Total
Total Flight time	Any type					
Multi-Crew Flight Time						
Single Engine Piston	SEP					
Multi Engine Piston	MEP					
Turbo-Prop						
Jet						

Glass Cockpit Hours: ______________________________________

FMS Hours: ____

POST-EXPERIMENT QUESTIONNAIRE

The purpose of this study is to design and evaluate a pilot cueing system for noise abatement approach procedures. All your information and answers will be confidential and anonymous. Your participation is voluntary. You may decline to answer any or all questions. You may decline further participation, at any time, without adverse consequences.

This questionnaire is designed to obtain your opinion of your performance and the experience you had during different trial runs. This questionnaire consists of two parts. The first part is a series of open-ended questions that allow you to describe your experience and performance. The second part is a set of specific questions that require you to answer by using a set of 7 rating scales and providing an explanation for your answers.

Open-ended questions:

1. What is the strategy that you use to meet the target with
    a. No Flap schedule?
    b. Flap schedule and without gates?
    c. Flap schedule AND gates?
2. If you must choose, would you describe your strategy as one or a combination of the following strategies: 1) using speed deviation at gates to make flap schedule adjustment; 2) relying on the last gates more than the first gates; 3) using a rule of thumb such as 10 knots/mile deceleration to manage the speed; 4) using the green arc to help you estimate the distance to decelerate; 5) using the deceleration arrow; 6) others
3. Were you able to detect the point where the aircraft would not be able to meet the target with recommended flap schedules? If so, when and how?
4. How did you adapt, if at all, the flap schedule to the speed deviations at gates? For example, how do you delay or "speed up" the next flap changes for a five knots speed deviation at a gate?
5. Do you have experiences of using these or similar strategies during flight? If so, in what circumstances and what are the similarities and differences?
6. Where do you think the gates should be placed along the descent?
7. Please describe a few ways in which you think a pilot procedure with gates can be integrated in the cockpit (in terms of presenting the information and providing procedures for PF/PM coordination)?
8. How do you think the controllers may upload gate information or wind information to pilots to perform a noise abatement approach procedure?
9. How may pilots object and/or support to the implementation/usage of gates?
10. How may controllers object and/or support to the implementation/usage of gates?

<u>Questions with a scale:</u>

1. How useful did you find the gates for the management of deceleration of the aircraft (as opposed to performing the same task without any gates)?

1	2	3	4	5	6	7

Not at all useful Very useful

2. How useful did you find the gates for achieving the target speed (as opposed to performing the same task without any gates)?

1	2	3	4	5	6	7

Not at all useful

Very useful

3. Did the task of managing the deceleration and meeting the target become more or less difficult as the number of gates increased?

1	2	3	4	5	6	7

Less Difficult

More difficult

4. How intrusive did you find the gates?

1	2	3	4	5	6	7

Not at all intrusive

Very intrusive

5. What effect, if any, did the gates have on your workload?

1	2	3	4	5	6	7

Decreased workload a great deal

Increased workload a great deal

6. How many gates do you prefer?

0	1	2	3	4	>4

And why?

7. Were the first gates as useful as the last gates?

1	2	3	4	5	6	7

Less useful More useful

And why?

8. How acceptable was the presentation of the gate?

1	2	3	4	5	6	7

Not at all
acceptable

Very acceptable

And why?

9. How acceptable do you find the gate method for managing the aircraft's deceleration?

1	2	3	4	5	6	7

Not at all
acceptable Very acceptable

And why?

10. How acceptable do you find the gate method for meeting speed constraints for noise abatement approach procedures?

1	2	3	4	5	6	7

Not at all
acceptable

Very acceptable

And why?

11. Please suggest some ways that the gates can be designed and/or implemented when the wind changes a) from head wind to tail wind; b) from tailwind to head wind.

Appendix D. General System Considerations for Designing and Implementing an ANAAP

Based on the results and lessons learned in this thesis, this guideline was composed to provide designers and policy makers general considerations for designing an ANAAP for a specific airport and aircraft and implementing it so that it fits in with the general context of how the ATC system currently operates.

1. Determine the need and constraints of the ATC operators: Study the SOP of ATC operation in TRACON and in centers that feed traffic to that TRACON. This includes types of arrival and departure procedures, types of aircraft, types of airline or air cargo, number of aircraft, traffic flow, ATC procedures and letters of agreement between center and TRACON, and coordination between center and TRACON. Study weather pattern, runway configuration, and runway surface operation. The output of this step is an ATC procedure for accommodating aircraft performing ANAAPs.
2. Determine the need of the community: Study the location where the noise reduction takes place. In some cases, some locations are more noise sensitive than others, and, hence, need special consideration (e.g. no thrust transients over these areas or direct flight track away from these areas). Integrate this study with an FAA Part 150 study, if one is currently in place. The output of this step is the noise intensity level and noise footprint along the intended flight track.
3. Determine the need of the airlines/air cargo: Study the noise benefits as well as reduction in fuel consumption and flight time. Determine the guidance and navigation capability of the aircraft and aircraft type. Determine the weight distribution of the aircraft. The output of this step is the designation of specific aircraft in the airlines' or air cargo companies' fleets performing ANAAP.
4. Synthesize the needs of the stakeholders and perform a tradeoff study to balance their interests. Based on these results, conceive and design a baseline procedure (see section 2.3). The output of this step is a baseline procedure, which includes the procedure parameters and the profile of the aircraft's states (e.g. the vertical, lateral, thrust, and speed profile).

5. For formal guidelines and criteria, the reader is referred to FAA Order 8260.48**,** Area Navigation (RNAV) Approach Construction Criteria; Order 7100.9D, Standard Terminal Arrival Program and Procedures; Order 8260.45A, Terminal Arrival Area (TAA) Design Criteria; and other relevant FAA orders.