HUMAN FACTORS IMPLICATIONS OF CONTINUOUS DESCENT APPROACH PROCEDURES FOR NOISE ABATEMENT IN AIR TRAFFIC CONTROL

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Abstract

Continuous Descent Approach (CDA) procedures can be effective at reducing aircraft noise in the vicinity of airports. The human factors implications for the air traffic controller of transitioning from conventional to CDA procedures are addressed in this paper. Different types of CDA procedures are introduced and models are developed of the controller tasks undertaken during current approach operations. The models are used to perform cognitive difference analyses to highlight the implications of using CDA procedures, particularly with respect to differences in intent, controllability and structure-based abstractions in the lateral, vertical and speed domains. An experiment is presented which probes the cognitive implications of changing speed profiles during the approach, which was one of the key differences between the procedures identified in the cognitive difference analysis. Based on the results, recommendations are made for CDA procedure design with a view to easing transition and controller acceptance.

1. Introduction

Growth in the number of air transportation operations is likely to be restricted unless the number of people significantly affected by aircraft noise is limited [1,2]. Although technological advances have made today's aircraft significantly quieter than older generations, modified operating procedures are likely to be required in order to achieve the noise targets of the future. One of the most promising operational techniques for noise abatement during approach flight phases involves Continuous Descent Approach (CDA) procedures that keep aircraft higher with lower thrust levels for longer than conventional approaches. This can reduce noise exposure on the ground by 3-6.5 dBA in some locations, a significant impact given that a 3 dBA difference represents a 50% reduction in acoustic energy. However, the use of CDAs can modify the way aircraft behave during approach operations which in turn can affect how they are to be managed by air traffic control (ATC). This paper focuses on human factors implications of the introduction of CDA noise abatement procedures.

2. Continuous Descent Approaches

2.1. CDA Concept

Conventional approach procedures typically employ periods of constant altitude and speed. These constant segments simplify the ATC tasks of spacing and sequencing traffic since they provide periods of well-defined vertical and speed behavior. When coupled to the use of tactical heading vectors to control an aircraft's lateral path, the air traffic controller can optimize traffic spacing and sequencing onto the final approach path and therefore retain control flexibility and make best use of the runway capacity.

The stepped altitude profile leads to aircraft spending periods of time flying level at low altitude near the airport and requires significant thrust input at each of the transitions to level altitude in order to arrest the descent. The combination of low altitude and frequent thrust transients leads to significant noise impact on the ground. By contrast, a Continuous Descent Approach aims to eliminate the level altitude segments and their associated thrust transients at low altitude. This keeps the aircraft higher and at lower thrust prior to intercepting the ILS, thereby reducing noise exposure on the ground below. A comparison of altitude profiles during a typical conventional procedure and a sample CDA is illustrated in Figure 1.

In addition to the changes in the altitude profile, the use of CDAs can also affect the way aircraft behave and are controlled in the lateral and speed axes relative to the conventional procedure. This depends on the type of CDA being flown, which can be broadly classified into two types: Basic CDAs and RNAV CDAs that are discussed in the following sections.

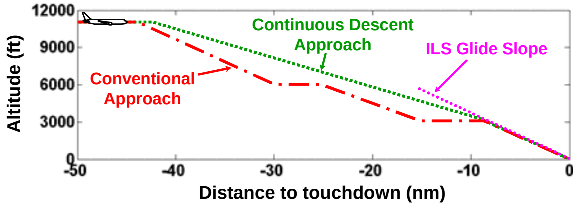

Figure 1: Conventional vs. Continuous Descent Approach Procedures.

2.2. Basic CDAs

In a Basic CDA (B-CDA) illustrated in Figure 2, the air traffic controllers retain the lateral control flexibility associated with using heading vectors. But unlike conventional approaches, during a B-CDA the controller also estimates the track distance to be flown by an aircraft given the chosen vectored path and issues these estimates to flight crew at various points during the approach (e.g. at 30 nm and 20 nm to touchdown). Flight crew use the track distance estimates to determine the appropriate descent rate for their aircraft in order to achieve a CDA, either with rules of thumb or flight manual charts. Tactical speed commands are still issued by the controller as in a conventional procedure, but the resulting aircraft speed behaviors could be different from a conventional procedure since a CDA is being flown.

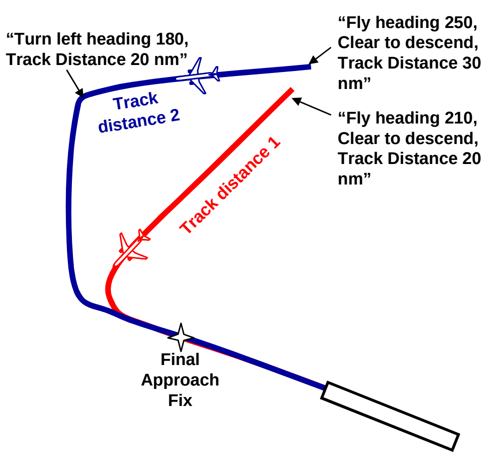

Figure 2: Lateral View of Basic CDA Concept.

Variants of the Basic CDA are operational at several major airports. For example, they have been used during night-time operations at London Heathrow for many years and can reduce noise by up to 5 dBA at 10-25 nm from touchdown [3]. However, experience also suggests that it is common for the track distance estimates to be quite uncertain [4]. This results in aircraft needing to level off if the track distance is under-estimated (making it similar to a conventional procedure) or needing more rapid descent rates than expected towards the end of procedure if the distance is over-estimated (leading to a rushed approach or need for a go-around). In either case, the noise benefits of the Basic CDA are reduced unless track distances can be determined accurately.

2.3. RNAV CDAs

A more advanced type of CDA involves a pre-defined trajectory of a series of waypoints with altitude and/or speed targets as required. These can be programmed into an aircraft's area navigation (RNAV) equipment such as the Flight Management System (FMS). This type of RNAV CDA is illustrated in Figure 3.

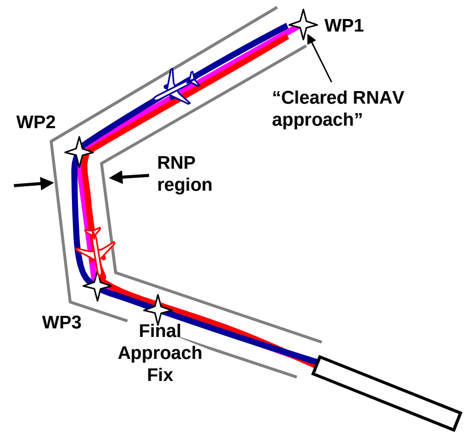

Figure 3: Lateral view of RNAV CDA Concept.

Track distances can be determined accurately since the waypoint locations are known. Descent rates can then be optimized in the procedure design or by the FMS such that level segments can often be eliminated entirely, gaining maximum environmental benefit from the CDA. Flight trials at Louisville in the US have demonstrated noise savings of up to 6.5 dBA with this type of RNAV CDA [5]. Additionally, since the lateral path is predetermined, all the aircraft flying the procedure can be constrained to a narrow path whose width is determined by the Required Navigation Performance (RNP) requirement level of the procedure. This enables noise exposure to be limited to these lateral regions, potentially avoiding highly populated or sensitive regions. However, because of the pre-determined nature of the trajectories, the procedure must be designed to be robust to a wide range of aircraft performance and environmental conditions (especially wind).

2.4. Control Implications of CDAs

Conventional, Basic CDA and RNAV CDA procedures have different implications for the way the aircraft are controlled in the lateral, vertical and speed domains, as summarized in Table 1.

Table 1: Control Implications of Procedures.

Procedure	Lateral Path Definition	Vertical Path Definition	Speed Definition
Conven-tional	ATC heading vectors	ATC altitude clearances	ATC speed clearances
Basic CDA*	ATC heading vectors	Pilot calc. or chart in manual *(after ATC descent clearance)*	ATC speed clearances
RNAV CDA*	FMS waypoint locations *(after ATC procedure clearance)*	FMS vertical targets *(after ATC procedure clearance)*	FMS speed targets *(after ATC procedure clearance)*

*Note: ATC can choose to abort a CDA at any time and revert to a conventional procedure.

In a conventional procedure, ATC has full path flexibility in all domains for each aircraft. In the Basic CDA, the controller has tactical flexibility over the lateral and speed domains while the specific vertical path is determined by the flight crew after the descent has been cleared and track distance given by ATC. In the RNAV CDA, path definition in all axes is defined by the FMS-based procedure after ATC clearance to fly it has been issued. In both CDA types, speed profiles can vary between aircraft due to performance differences, FMS logic and environmental conditions. The human factors implications of the differences outlined above must be carefully considered so that controller workload and performance are not unduly affected.

3. Controller Tasks During Approach Operations

A CDA approach can involve en route, terminal area (TRACON) and tower controllers depending on the height at which the procedure starts. For the purposes of this paper, only the TRACON approach controller will be considered, because they are most directly affected by any procedure transition.

An ATC Process Control Model shown in Figure 4 was created to better understand the controller's processes in separating aircraft on approach. This model was initially formed based on Endsley's situation awareness model [6] and Pawlak's decision process model [7]. It was modified by consulting the Air Traffic Control manual [8] and standard operating procedures at Boston and New York TRACONs. Further modifications were made after a series of site visits to Boston, Manchester NH, New York and Reykjavik approach control facilities.

The ATC Process Control Model depicts a representation of the controller's cognitive processes and their interaction with the environment. The following subsections discuss each of the system elements with respect to the final approach controller.

3.1 Information System

The approach controller has several sources of information available to him or her. One source is the radar display, from which the controller can retrieve lateral position information (aircraft, runway, navaids, and other environmental landmarks), groundspeed, aircraft ID, altitude, and aircraft type. The information update is not continuous, however, and is constrained by the rotation rate of the radar, which is 4.8 sec for most TRACONs in the U.S.

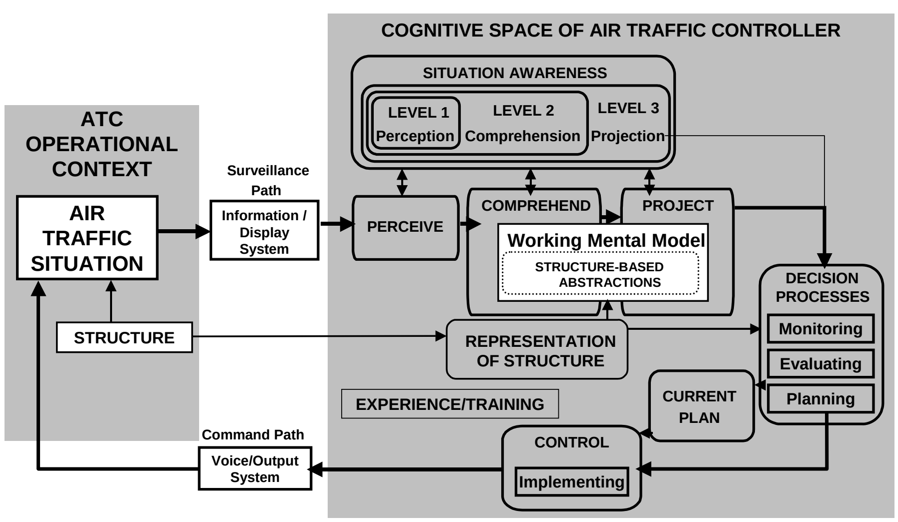

Figure 4: ATC Process Model.

A second important source of information are VHF communications with the pilots. From these communications, the pilot informs the controller that he or she understands instructions through clearance readback. Communications also reveal when the pilot has traffic or runway "in sight", allowing the controller to delegate separation control to the pilot. PIREPs, altitude verifications and emergency information are also delivered through VHF communications.

Another key input to the approach controller's task is the "structure" of the approach environment. Structure is defined as a set of constraints (either physical or human-imposed) that limits the evolution of the dynamics of the system. Examples of physical structure include runways, navigation aids, terrain or obstructions. Examples of human-imposed structure include airspace boundaries, procedures and standard flight levels. In a conventional approach, the ILS beam, Standard Arrival (STAR) procedures, and ATC Standard Operating Procedures (SOPs) are critical elements of structure. An example of an approach SOP is depicted in Figure 5.

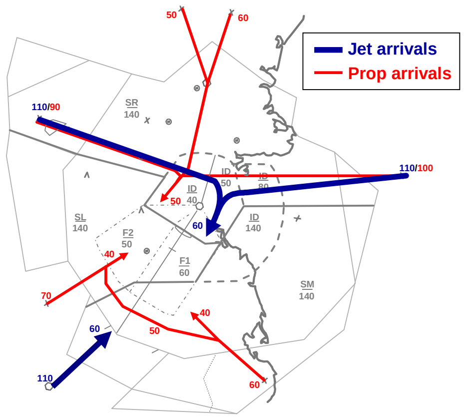

Figure 5: Boston Arrival SOPs for Runways 4R/4L. (Courtesy BOS TRACON Training)

Each of these examples of structure establishes constraints such that, if violated, either physical or system laws will have been broken. The structure is a pilot-controller shared information set so the controller can expect the aircraft to remain within the constraints under normal circumstances.

3.2 Situation Awareness Processes

As the approach controller observes the various inputs from the environment, this data is transformed into situation-relevant information through a set of cognitive processes that contribute to Endsley's concept of "situation awareness" [6]. Data from the information sources are *Perceived* through auditory or visual modalities. This information is then *Comprehended* and *Projected* into the future.

Figure 6 depicts an expansion of the Comprehension process. In this process, information from the display is filtered and integrated with information from training and experience to develop an understanding of the current air traffic situation. It is also informed by and informs the working mental model, which is defined, in this case, as a model of the situation and its dynamics created by the controller for projection use in the context of the task.

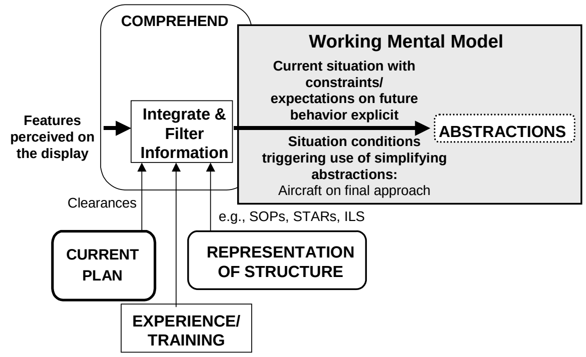

Figure 6: Comprehension Process.

As indicated in the figure, information about structure and clearances given contribute to this formation by partially specifying the aircraft's intent. Intent, in this context, is defined as a controller-pilot shared plan of the aircraft's trajectory into the future. Clearances are a contract between the controller and the pilot about the aircraft's future trajectory. Often, an aircraft is cleared to proceed using a particular procedure (e.g., "Cleared ILS 4R"). This clearance indicates that the controller and pilot agree on a precise lateral and vertical flight path limited by the structure imposed by the ILS localizer and glideslope. Other clearances may only specify a desired state until further commands are issued (e.g., "Reduce speed to 240 kts."). This allows the controller to impose control on the aircraft in situations in which intent is not defined or is unclear. Knowledge of the current situation and the limitations of evolution allow the controller to apply dynamic abstractions for use in the projection process.

The projection process is particularly important to controllers due to the time delays inherent in the ATC surveillance/control loop. Figure 7 depicts how the controller integrates two levels of projection to develop his or her overall situation projection. The comprehension stage provides current situation information and accesses dynamic abstractions that form the working mental model. In the projection stage, the current situation is propagated forward in time using the abstractions in the working mental model. The basis for the projection is a Simple Extrapolation that uses past position information to predict future position.

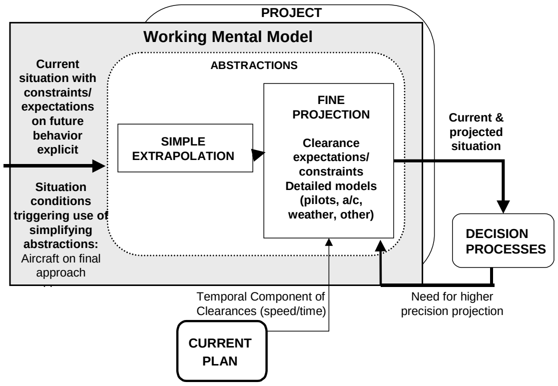

Figure 7: Projection Process.

Fine projection involves the incorporation of more detailed behavioral models and temporal constraints on dynamics into the projection. Precision requirements from the Decision Processes determine what modifications to the Simple Extrapolation should be included in Fine Projection, which influence how detailed the situation projection should be.

In the conventional approach, lateral and vertical trajectories are defined in the STAR & SOPs. Thus the longitudinal axis is the primary control dimension on approach and is the dimension along which tactical projection is required. Control is imposed on the speed dimension through speed state controls (e.g., "Decelerate to 240 kts."), and therefore the speed profile is delineated into periods of non-transitional speed combined with short periods of speed transition.

Thus, the Simple Extrapolation longitudinal projection mechanism is a constant velocity longitudinal extrapolation. Constant velocity extrapolation is a projection based on past position information in which the controller uses estimated distance traveled over the most recent update to propagate the aircraft position over the same distance at the next update. Whether the information used in extrapolation is sufficient for the separation task depends on whether an adequate rate of change estimate can be established to capture the aircraft dynamics to the precision required for the evaluation against separation standards.

Fine Projection modifications can be made with knowledge of a deceleration clearance. Instead of projecting equal distance between updates, the controller projects a slightly shorter distance than the previous update, the distance difference based upon his or her particular deceleration abstraction. Another Fine Projection modification used in approach operations is a wind abstraction. In addition, speed clearances or time-over-fix clearances may also constrain the evolution of the system. Depending on the precision required of the projection at the Decision Processes stage (e.g., a situation in which the controller is only managing 1 aircraft), these detailed modifications may not be required.

As projection extends into the future, uncertainty increases, requiring different projection techniques. An adapted version of Vigeant-Langlois's [9] uncertainty framework is shown in Figure 8. Over a very short projection time (e.g. less than one update cycle), the aircraft can be assumed to be in the same location on the radar screen.

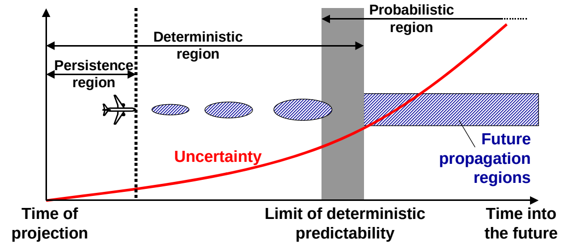

Figure 8: Effect of Time on Longitudinal Projection Process. (Adapted from [9])

Over slightly longer times (e.g. a few position updates into the future), a deterministic projection can be made using cognitive models of the dynamic behavior of the elements in the situation compiled into a working mental model. The constant velocity extrapolation is an example of a simple dynamic model.

At some point in the future, deterministic models break down, and alternatively, stochastic models are used. Intent plays an important role in determining the limit of deterministic predictability. Knowledge of intent constrains the future aircraft trajectory, extending the time into the future that a deterministic projection can be made (pushing the limit of deterministic probability in Figure 8 to the right). The periods of non-transition in the longitudinal structure in the conventional approach allow the constant velocity structure-based abstraction to be an accurate projection further into the future. In Figure 8, the example shows a longitudinal projection constrained by lateral intent knowledge, however different limits of deterministic predictability can be present in different axes, influenced by the intent information in that axis.

3.3 Decision Processes

Based on the controller's projection of the situation dynamics, the controller monitors the information to determine whether it corresponds with his or her "current plan", which is an internal cognitive state. This is the controller's time-dependent schedule of events and commands to be implemented as well as the resulting situation evolution and aircraft trajectories that will ensure that the air traffic situation evolves in an efficient and conflict-free manner. If the projection of the situation does not match the plan, the controller evaluates whether the situation evolution meets the task constraints. If the projection is found to be unacceptable, the controller then plans an action or set of actions on the system that will return the situation behavior within acceptable bounds, modifying the "current plan".

Accuracy and precision of the projection can vary depending on the fidelity of the working mental model used to perform the projection and the information available to make the projection. The requirements on the projection are set by the restriction against which the projection is evaluated. For example, different projection requirements exist for a situation in which an aircraft's separation from another aircraft on approach directly in front is being evaluated as compared to a situation in which a controller is evaluating crossing time over a waypoint.

Developing a plan that satisfies all of the constraints that controllers must meet can be very complicated, however structure allows the simplification of the evaluation and planning tasks. Procedures like the approach SOPs are specifically constructed to ensure that separation constraints are met between highly interacting traffic flows. If the default current plan is to follow the SOP and the STAR on approach, the sequence of descents and heading vectors is already established depending on the type of aircraft.

3.4 Control

Once the current plan has been created, the controller must then execute the actions of this plan. The primary means of ATC plan execution is through VHF radio communications to the pilot. In ATC there is a fundamental limit on the controller's ability to respond to the system in a timely fashion due to the system cycle time and the controller's dependence on the pilot to execute commands quickly and accurately.

In the TRACON environment, there are several types of control actions that the controller can implement. A discrete control command signals ATC authorization to begin a standard or approved procedure. For example, "Cleared ILS 4L" is a discrete command. The controller can execute fine control over the aircraft by using state control clearances such as "Fly heading 270" or "Descend to 4000 ft". Approach controllers can also provide state constraints to the aircraft, such as "Descend to (altitude) by (waypoint)" or "Cross (waypoint) at (time)."

By having developed expert models of the aircraft dynamics, controllers can also achieve a desired state in one axis while controlling another axis through an indirect control command. An example of this is meeting a time-over-fix requirement through speed vector commands.

Control provides another means by which future aircraft behavior uncertainty can be reduced. If a controller is projecting future aircraft state in the probabilistic region in Figure 8, a state constraint or command can be issued to clarify intent of the aircraft and maximize the accuracy of the projection.

4. Cognitive Difference Analysis

Using the ATC Process Model as a framework for understanding the controller's task during a conventional approach, cognitive differences between the conventional approach and the Basic and RNAV CDA approaches were identified. The three cognitive areas in which the CDA procedures most significantly differ from the conventional approach include *Intent*, *Controllability*, and *Structure-Based Abstractions*. Each of these areas of potential cognitive dissonance is discussed in the sections below.

4.1 Intent

In the conventional approach procedure, aircraft generally follow standardized trajectories outlined in the Standard Terminal Arrival Routes (STARs) or ATC facility Standard Operating Procedures (SOPs). These procedures describe the expected behavior of the aircraft in lateral, vertical, and speed dimensions that is shared with the controller. They provide the structural base patterns which support the controller's tasks of perceiving, comprehending, projecting, and monitoring. As in Figure 6, intent information also allows access to dynamic abstractions, simplifying the projection process. The procedures simplify the controller's tasks of evaluation and planning because they are specifically designed to separate the major traffic flows.

The Basic CDA procedure modifies the SOP and STAR structure in at least the vertical dimension. Because the Basic CDA procedure requires the pilots to plan the vertical trajectory based upon aircraft type and reported track distance from the runway, each individual aircraft may exhibit a different descent profile. Considering Figure 7, because vertical stable periods are removed, the aircraft's longitudinal behavior may be complicated due to vertical transition interactions, making the constant velocity abstraction unreliable. Instead, pair-wise comparisons of separation between aircraft must be projected to assure required separation, compounding ATC workload. If separation becomes a problem, the controller will also be constrained to ensuring that any trajectory modifications are conflict-free in the lateral and speed dimensions when planning due to the CDA vertical structure requirements.

The RNAV procedure is structured in all three dimensions through an FMS profile to optimize descent rate and meet altitude and airspeed constraints. Detailed trajectory intent information is available to pilots through the FMS that is not available to the controller with current ATC technologies. Depending on how the procedure is created, it can be consistent with the non-interacting flows of the SOPs and the STARs. In a situation in which the RNAV procedure is consistent with the SOPs and STARs, the controller may be able to rely on the safety of non-interacting flows to compensate for the constant velocity abstraction unreliability. Because of the non-interacting design, the controller's evaluation and planning process is similar in difficulty to the conventional procedure. If the procedure is inconsistent with the SOPs and STARs, the cognitive difficulty would increase unless the controllers could develop a mental model of the new pattern.

4.2 Controllability

As previously discussed, the conventional approach allows a variety of control actions to be performed on the traffic flow including discrete control, state control and constraint-based control. The controllers have the ability to alter the aircraft's lateral, vertical, and speed trajectories.

Unlike the conventional approach, the Basic CDA procedure passes vertical path determination to the flight crew, who establish a CDA-compliant descent rate. The controller retains full path determination in the lateral and speed dimensions. The controller is also provided with an additional control of "track distance", which the pilot uses to identify the appropriate CDA descent rate. In this way, the controller is able to use indirect control over the vertical dimension. This indirect control was used by the controllers to ensure a conservative (safe) altitude profile in the analyses by Kershaw, *et al.* [4].

In the RNAV procedure, controllability is almost completely removed from the controller. Controllers are only given discrete control over the aircraft trajectories performing the noise abatement procedure. The controllers clear the aircraft to begin the approach, and the pilot then executes the FMS-controlled approach. Tactical state control is removed from the controller, preventing any fine control of aircraft behavior to ensure separation. However, if controllers determine that action should be taken to prevent a conflict, the controller can remove the aircraft from the RNAV approach and resume a non-CDA conventional approach or command the aircraft to perform a go-around procedure.

The controller's ability to reduce intent uncertainty appears to be diminished in each of the CDA procedures, as indicated in Table 1. Similar to the structure issue, controllers may be unable to effectively reduce the uncertainty of projection in the probabilistic regime.

4.3 Structure-Based Abstractions

Controllers using conventional approach procedures are able to simplify their projection processes through the use of non-transition periods, especially constant speed, to maximize the accuracy of their extrapolations. The use of non-transition speed periods of flight were used to establish a pattern of position change of the radar blips and project using a cognitive pattern-matching mechanism.

In both CDA procedures, vertical non-transition periods are lost due to the requirement of continuous descent for noise purposes. Thus, the vertical projection process could be made more difficult by the lack of non-transitional periods. In the RNAV procedure, the non-transitional speed period is also lost to the control of the aircraft FMS.

Simple structure-based abstractions of constant speed and non-transitional periods appear to be reduced or removed in the CDA procedures. It is unclear whether controllers are able to develop new structure-based abstractions of deceleration patterns to aid them in their projection.

In order to better understand the ability of the controllers to develop new structure-based abstractions based upon deceleration patterns, an experiment was performed to investigate one of these structure-based abstractions—constant speed.

5. Experimental Investigation of Benefits to Constant Velocity Structure

In the Cognitive Difference Analysis, periods of constant speed were hypothesized as being a key

Structure-based Abstraction mechanism for improved projection performance. An experiment was performed to test this hypothesis by comparing the projection accuracy of aircraft separation tasks involving constant and decelerating aircraft combinations.

5.1 Participants

8 French student air traffic controllers with an average of 1.25 years experience participated in this experiment. Five of the controllers were two months from being certified as approach controllers and 3 were in their final stages of training to be en route controllers.

5.2 Experimental Task

Participants were asked to view a low-fidelity PC-based simulation of a final approach scenario with pairs of aircraft proceeding down a straight path, as depicted in Figure 9. Controllers were shown the position of the aircraft on the flight path as well as the current ground speed of the aircraft, which varied between 300 and 150 kts. The update rate of the position mimicked the TRACON surveillance radar rate of 4.8 sec. At three points along the path, controllers were asked to make a projection of the aircraft pair's separation at the end of the flight path by mouse-clicking the location of the trailing aircraft when the leading aircraft passed the final threshold.

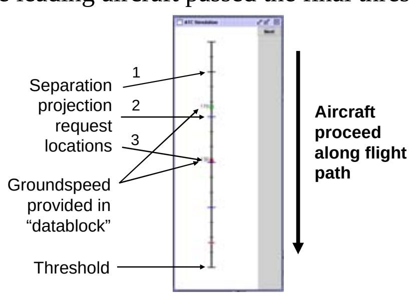

Figure 9: Experimental Display.

5.3 Independent & Dependent Variables

The speed profiles of the aircraft pair were varied in this experiment. The aircraft were either both decelerating, both proceeding at constant speed, or one aircraft was decelerating and the other was proceeding at constant speed. The latter scenario will be termed a "mixed" profile scenario. Deceleration profiles were all linear between a start and end speed.

The end speed of the aircraft was also varied in this experiment. Typical end speeds were 150 or 160 kts, representative of an aircraft on final approach. The exception was in the decelerating/constant case, in which in order to be able to observe the separation change of the aircraft at all three projection points, the end speeds of the trailing aircraft in this scenario were required to be slightly higher at 180-190 kts.

The separation of the aircraft pair could either be decreasing along the flight path (a "closing" case), increasing along the flight path (an "opening" case), or the speeds could be the same (in the both constant speed cases). 25% of the scenarios involved both constant, 25% involved both decelerating, 25% involved an opening case, and 25% involved a closing case.

Final separation of the aircraft was counterbalanced across the scenarios, ranging between 1-6 nm. The exception, again, was in the decelerating/constant scenarios in which the scenario dynamics required between 10-12 nm separation at the threshold to allow observability during the projection periods.

Accuracy of the projection and improvement of the accuracy over time were measured in this experiment. Accuracy of the projection was defined as the difference between the actual separation and the recorded projection of the aircraft when the leading aircraft passed the threshold. Accuracy over time was measured by comparing the differences over the three points of projection requested in a scenario.

Questionnaires provided at the end of the experiment elicited subjective responses to the question: "What was your strategy for predicting separation in this task?"

5.4 Results

Projection accuracy analysis for the third projection was performed because controllers were given the longest time to observe the aircraft behaviors until the projection was made. Figure 10 depicts the projection accuracy results for this analysis. The difference between actual and projected separation is depicted as a function of the relative speeds of the aircraft pair for each of the speed profiles. Three speed profiles were biased toward negative difference values, i.e. towards estimations of less separation than actually was present. This indicated that the controllers tended to be conservative (safe) in their separation projections. In the decelerating/constant profile, the "risky" behavior resulted from the fact that the final separations were significantly larger (at 10-12 nm) than the other scenarios (at 1-6 nm) due to the dynamics in that scenario. No data was available for the decelerating/constant "equal" and "opening" cases due to the dynamic constraints of the scenario.

There was no significant difference between the both constant and both decelerating cases, however there was a significant difference between the both decelerating case and the constant/decelerating scenario (closing case: t=2.021, p<.05, equal case: t=1.279, p<.15). The average difference between the constant/decelerating scenario was significantly more "conservative" possibly due to the controller's inability to predict the mixed scenario accurately, therefore erring the estimation on the conservative side. No significant difference was found between the closing and opening cases of the constant/decelerating scenario.

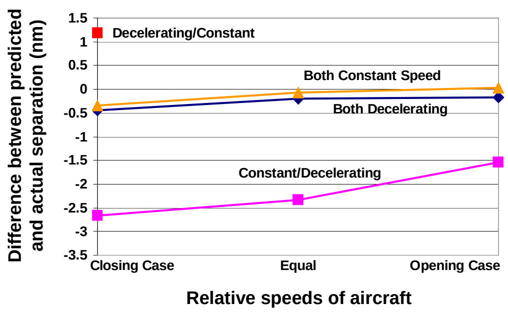

Figure 10: 3rd Projection Accuracy Results.

Analyzing projection accuracy over time, as depicted in Figure 11, the data suggest that projection accuracy marginally improved over time in the mixed profile scenarios. Accuracy was lower in the decelerating/constant profile scenarios at projection 1 (t=3.774, p<.0005) and projection 2 (t=1.973, p<.05). No improvement was apparent in the both decelerating or both constant speed scenarios. In a similar situation as the previous analysis, the decelerating/constant case resulted in "riskier" separation projections due to the significantly larger final relative separation over the other speed profiles. No data were available for the constant/decelerating projection 1 due to the scenario dynamics.

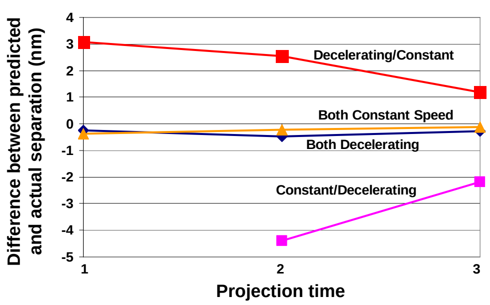

Figure 11: Projection Accuracy Over Time.

The subjective results from the questionnaire indicated that 6 of the 8 participants described sampling the separation at two different points, then estimating a final separation based upon the rate of change of the relative separation.

5.5 Significance of Results

Projection accuracy of the mixed profile scenarios was significantly worse than when projecting either both constant or both decelerating aircraft. There was no difference in accuracy comparing both decelerating and both constant projections. These results suggest that if there is a structure-based abstraction that allows higher extrapolation accuracy of constant speed, the same or a similar abstraction is created and used when projecting both decelerating aircraft.

One possible explanation of the structure-based abstraction involves the key variable being projected in this experiment, namely relative separation. Figure 12 shows that the relative separation of both constant speed aircraft is constant. The relative separation of both decelerating aircraft in this experiment approximates a linear function. The relative separation in the mixed profile scenario is a non-linear function. Since it was established from the subjective reports that the controllers developed a dynamic model of changing relative separation, it appears that they were more able to internalize the constant and linearly changing relative separation over the non-linear change in relative separation.

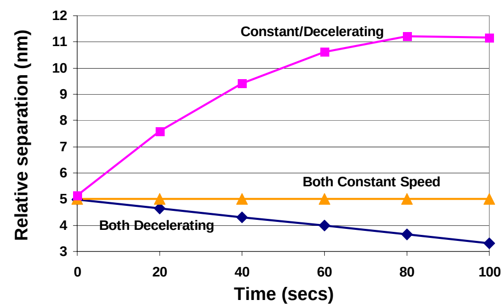

Figure 12: Relative Aircraft Separation.

A limitation of this experiment is that only linear deceleration profiles are used, and this hypothesis should be confirmed using non-linear deceleration profiles for purposes of realism. However, if controllers are just as easily able to internalize the dynamics of a both decelerating aircraft scenario (assuming standardized decelerating profiles) as they are a both constant aircraft scenario, then the implications for CDA procedure design are great.

6. CDA Design Guidance & Conclusions

Based upon the findings from the Cognitive Difference Analysis and the Experimental Investigation, recommendations and considerations for the design of CDA procedures can be provided to minimize the cognitive difficulties in transition.

A tradeoff exists between the design of CDA procedures to minimize the impact of noise on the communities and providing enough aid to the air traffic controller who is responsible for the safety of the aircraft and surrounding traffic. Standardization of CDA deceleration profiles may be able to take advantage of several of the adaptation mechanisms that the controllers have developed. As discovered in the experimental investigation, standardization of deceleration profiles would allow the use of structure-based cognitive abstractions which are similar in performance to constant velocity structure-based abstractions which are currently used to simplify the working mental model used in controllers' future longitudinal state projection. This simplifies the projection because the intent is explicit, reducing the uncertainty and offsetting the reduced speed control that is currently used to manage longitudinal intent. However, further research needs to be performed using realistic deceleration profiles (as opposed to linear profiles) and to determine if, given different aircraft types and environmental factors, standardized deceleration profiles are possible.

It is also useful to simplify the controller's evaluation process by designing the standardized CDA procedures to be non-interacting across merging traffic flows. As long as the aircraft are conforming to the expected procedure laterally, vertically, and longitudinally, the controller can be assured that separation is met because the procedures were designed in that way.

Another issue to address in CDA procedure design involves the level of responsibility that is delegated to the controller. In procedures that require precise trajectories and many constraints, it may be best to delegate fine control of the trajectory and tactical separation assurance to the pilot. This delegation best suits the situation due to the surveillance and command delays inherent in the control loop and the location of precise intent knowledge in the FMS-driven procedures.

In conclusion, CDA procedures provide a near-term improvement to the problem of noise in the terminal environment. By designing the procedures to compensate for removal of critical structure-based abstractions, system performance is enhanced while minimizing transition issues with the controllers.

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References

[1] UK Dept. for Transport White Paper, "The Future of Air Transport: Summary", www.dft.gov.uk, Dec. 2003.

[2] US Dept. of Transportation, "Aviation Noise Abatement Policy 2000", Federal Register, Vol. 65, No. 136, Jul. 2000.

[3] UK Dept. of the Environment, Transport and the Regions, Final report of the Aircraft Noise Monitoring Advisory Committee Technical Working Group, "Noise from Arriving Aircraft: Summary", Mar. 2000.

[4] Kershaw, A. D., Rhodes, D. P. & Smith, N. A., "The Influence of ATC in Approach Noise Abatement", *3rd FAA/Eurocontrol Air Traffic Management Conference*, Naples, Italy, Jun. 2000.

[5] Clarke, J-P. B., Ho, N. T., Ren, L., Brown, J. A., Elmer, K. R., Tong, K-O & Wat, J. K., "Continuous Descent Approach: Design and Flight Test for Louisville International Airport", *Journal of Aircraft*, Vol. 41, No. 5, 2004, pp. 1054-1066.

[6] Endsley, M., "Toward a Theory of Situation Awareness in Dynamic Systems", *Human Factors*, Vol. 37, No. 1, 1995, pp. 32-64.

[7] Pawlak, W. S., Brinton, C. R., Crouch, K. & Lancaster, K. M., "A Framework for the Evaluation of Air Traffic Control Complexity", Paper AIAA-1996-3856, *AIAA Guidance, Navigation & Control Conference*, San Diego, CA, Jul. 1996.

[8] FAA, "Air Traffic Control", FAA Order 7110.65M, www.faa.gov/ATpubs/ATC, Washington, DC, 2000.

[9] Vigeant-Langlois, L. & Hansman, R. J., "Human-Centered Systems Analysis of Aircraft Separation from Adverse Weather", *Ph.D. Thesis submitted to the Dept. of Aeronautics & Astronautics*, MIT, International Center for Air Transportation Report No. ICAT-2004-2, Jun. 2004.

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Noise abatement procedures, continuous descent approach, human factors, projection.

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