MANAGEMENT OF CONTINUOUS DESCENT APPROACH DURING INTERVAL MANAGEMENT OPERATION

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Abstract

This paper reports on the performance and workload of pilots participating in a human-in-the-loop simulation of interval management operations during a continuous descent approach (CDA) into Louisville International Airport (SDF). The experiment examined variations in pilot roles and responsibilities in an implementation of interval management automation.

The roles and responsibility manipulation showed that whether pilots were instructed to follow speed guidance strictly, or to exercise their own judgment, had no effect on workload and only a small effect on interval management performance. However, requiring the pilots to manually enter speeds into the autopilot, rather than having the automation automatically update the autopilot, frequently led to poorer energy management, and higher spacing interval errors at the final approach fix, even in the conditions where pilots were instructed to strictly follow speed guidance. This finding was traced to poorer compliance with the automated speed guidance, lack of awareness of this poor compliance, and insufficient awareness of the energy state of the aircraft. These results suggest that some form of energy guidance may be needed to augment interval management. To do this, recommendations were made for integrating the spacing interval management automation with near-term or far-term energy management systems.

Workload measurement showed that, when pilots were required to maneuver to avoid en route weather, the manual conditions resulted in an increase in workload, although the overall level would still be considered low under normal circumstances.

Introduction

The Next Generation Air Transportation System (NextGen), an initiative spanning multiple federal government agencies and the aviation industry, seeks to modernize how air traffic is handled and to increase the overall efficiency and safety of the system [1]. The JPDO recognizes that achieving increased safety, efficiency, and capacity goals for the National Airspace System (NAS) by 2025 will require more support from automation. In response, the FAA and NASA are examining a variety of advanced ground and flight deck automation tools, including tools to support approach and arrival operations into and through congested terminal airspace [2- 4].

This paper focuses on a proposed concept of operation in which controllers have delegated the control of speed to appropriately equipped flight decks during continuous descent approaches (CDAs) from cruise altitude. CDAs are a new type of descent designed to reduce noise, emissions, and fuel use by having aircraft descend continuously rather than in the series of steps which is customary today.

In these proposed operations, pilots oversee the spacing between their aircraft and their assigned lead aircraft while conducting CDAs. Such operations are known as interval management. Interval management involves the merging and spacing of aircraft as they approach the airport in order to achieve scheduling goals [5], and is sometimes referred to as “merging and spacing” for this reason. Merging applies to aircraft that are attempting to achieve an in-trail position behind an assigned lead aircraft approaching from another traffic stream [6]. Spacing occurs when aircraft try to achieve, and/or maintain, a specified longitudinal or temporal distance from an assigned lead aircraft.

Prevot [7] compared the use of flight deck interval management automation with ground-based automation for interval management during arrivals. For the flight deck option, lead aircraft assignments were sent from control stations to flight decks via digital communications (datacom); in the ground-based option, the controllers had the automation tools to help them determine speed clearances. Pilots using flight deck automation loaded the datacom delivered spacing intervals and

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assigned leads into the automation, which in turn adjusted aircraft speed to first achieve, then maintain, the desired target spacing interval. This automation also provided visual feedback indicating the status of the current spacing interval relative to the targeted one. Prevot found a significant improvement in interval management performance when advanced flight deck automation was present.

Researchers at the NASA Langley Research Center have also been highly active in a similar effort [8]. In particular, they have developed and tested advanced flight-deck-based automation called Airborne Spacing for Terminal Arrival Routes (ASTAR). Its goal is to optimize throughput by bringing aircraft to the runway threshold with a specific and reliable time in trail. ASTAR can be contrasted with most other approaches to interval management, such as the one used by Prevot et al. [2, 7]. The other approaches are based on an aircraft attaining and maintaining a longitudinal or temporal distance behind another aircraft. Thus, if the goal was to be 120 seconds in-trail of a leading aircraft (i.e., about eight miles at the entry to the terminal area) a pilot would try to achieve and maintain this interval. ASTAR, on the other hand, assumes all aircraft should be attempting to fly a fixed speed profile (specific schedule of speeds) along their common arrival route, and is constantly commanding speed adjustments in order to position the aircraft to 1) arrive at the final-approach-fix at an assigned time in trail of their lead and 2) to fly the profile speeds in between these adjustments. See Abbott [9] for more details on the algorithm.

Computer based fast-time simulations have shown that good interval management performance can be achieved with airborne-based ASTAR spacing automation [4]. Improved interval management performance was also found when pilots were trained to strictly follow ASTAR automation guidance to execute aircraft-to-aircraft interval management tasks [8, 10]. In general, interval management with support from flight deck spacing automation has been found to be feasible under nominal conditions, but the ability to modify planned routes and continue to achieve spacing goals needs to be examined [4]. Route modifications can occur in response to traffic conflicts or hazardous weather. Further, to date, all fast-time simulations have taken steps to insure that the algorithm's recommended speeds are strictly adhered to. It is not clear the degree to which such adherence is necessary or even desirable (e.g., a pilot may have information or requirements unavailable to the automation such as a need to deviate for weather). The goal of this paper is to investigate how automation can be deployed on the flight deck to improve interval management operations during the arrival phase of flight, and assess the robustness of these operations to the vicissitudes of human behavior and off-nominal events (i.e., the presence of weather).

Current Study

The current study was a multi-participant distributed simulation experiment that examined the robustness of interval management during CDAs along the CBSKT 1 Arrival into SDF. Managing both goals can be seen as a difficult energy management task, where the spacing operation, maintaining a CDA, and the need to meet speed and altitude restrictions along this approach, all must be balanced. Because ASTAR is based around the use of the CDA profile, it appears to be very well suited to this type of operation, and indeed, it has been shown to accomplish this very well [8].

The primary focus of this study was the examination of how well pilots could manage these CDAs and interval management while using ASTAR automation implemented in such a manner as to allow for different levels of pilot involvement. As previously mentioned, studies using ASTAR have used fast-time, fully automated, non human-in-the-loop evaluations [4], or have trained pilots to rigorously and strictly follow automated guidance [8, 10]. In contrast, this study focused upon how factors related to the division of roles and responsibilities between the pilot and the automation (ASTAR) would affect spacing performance. Specifically, a *Speed Control* manipulation determined whether the speeds calculated by the automation had to be manually entered into the autopilot (Manual Speed Control); or if an option was available to automatically implement speed guidance (Automated Speed Control). A *Pilot Instruction* manipulation determined whether the pilot was told to faithfully follow automated speed commands (Follow Speed Command); or was given the latitude to overrule/augment this automated guidance with his or her own judgment (Pilot Discretion). It was anticipated that pilots in the Pilot Discretion condition would insert their own judgment. If pilots did insert their own judgment, we were interested in if this might lead to trouble managing the two tasks due to the complexity of the energy management, or if pilot expertise would actually improve this management. Similarly, the Speed Control manipulation was included because both modes of operation are under active consideration in NextGen and we wanted to determine if one led to superior outcomes in this study compared to the other.

In addition to the above manipulations, a *Weather* manipulation was used to examine the impact of avoiding en route weather on CDA performance and workload. The simulated, experimental flights reported in this paper began en route and included an en route weather avoidance task. While this paper does not report on the en route data, it was found that route modifications required to avoid the weather would perturb the initial spacing task, and thereby generate challenges for subsequent CDA operations. An analysis of the en route weather avoidance operations can be found in a companion paper [11]. Other than the above procedures, the procedures used in the study were similar to those used by Prevot [7].

This study used the Cockpit Situation Display (CSD), an advanced integrated display of traffic and weather developed at the Flight Deck Display Research Laboratory (FDDRL) at NASA Ames Research Center [12]; and the flight deck based ASTAR automation, developed at NASA Langley Research Center. The study utilized a distributed simulation in which eight commercial pilot participants at the Flight Deck Display Research Laboratory (FDDRL) at NASA Ames Research Center flew desktop 747/757-like simulators. California State University Long Beach provided confederate air traffic control operations, and pseudopilot operations were conducted from California State Universities Long Beach and Northridge, and from Purdue University.

Methods

Participants

Eight commercial transport pilots with glass cockpit experience were recruited for this simulation experiment. They were compensated $25/hr for their participation.

Apparatus

Participants interacted with simulation software on single-pilot desktop PCs using standard keyboards and mouse inputs. Two pieces of software composed the pilot's main simulation environment – the Multi-Aircraft Control System (MACS) and the 3D Cockpit Situation Display (CSD). The MACS system (Figure 1, upper panel) provided pilots with an interface that allowed flying their aircraft with tools normally found in current day Boeing 747/757 aircraft [13]. A window on the MACS interface displayed spacing clearances (aircraft to follow, and interval time in trail) sent by a confederate air traffic controller. This window also had buttons that allowed pilots to acknowledge successful clearance arrival, and then to automatically load (or reject) this clearance. Pilots manipulated aircraft speed using typical 757/747 speed controls and displays simulated by MACS. Figure 1, lower panel, shows enlarged view of this part of the MACS display, with the commanded speed window and control.

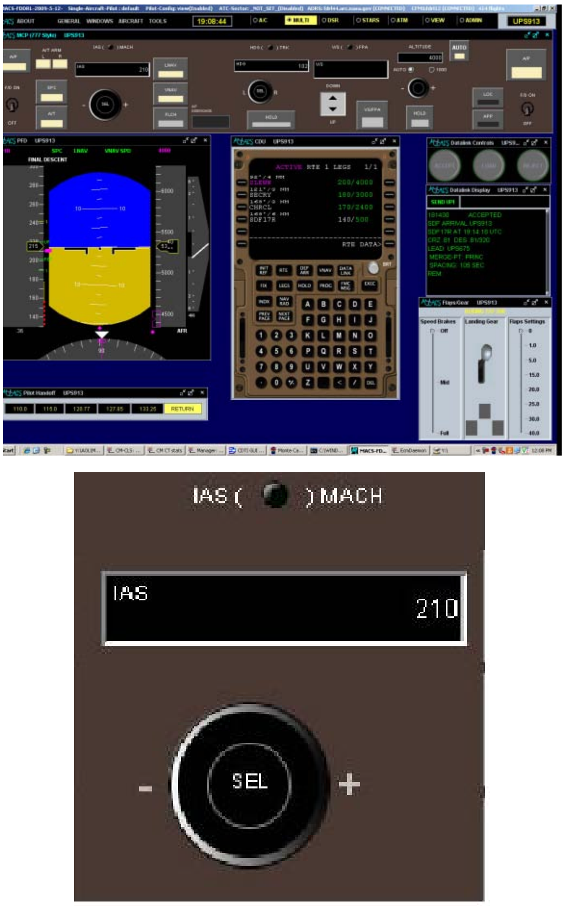


Figure 1. MACS Interface

The CSD (shown in 2D mode in Figure 2) provided pilots with a display of traffic and weather, plus advanced conflict detection and resolution (CD&R), flight path replanning, and interval management tools. The CSD provided an adjustable view of traffic up to a 160 nm radius and a simulated airborne weather display with a tilt control. With the exception of weather, in this experiment the CSD could display all information in 2D (top down or profile) or in 3D views. Additional details regarding the CSD's capabilities are described by Granada [12]. In addition, automated spacing tools were integrated into the CSD. When prompted by spacing clearances, pilots loaded the clearance into the spacing tool, and then engaged the spacing automation. At this point a "spacing box" was shown with color coding that reflected the Ownship's spacing status (Figure 3, lower panel). If the nose of the Ownship icon was within the box, then spacing performance was considered within tolerance (i.e., close enough). In this case, the spacing box was green. On the other hand the box was coded white if Ownship (in magenta) was behind the box and yellow if Ownship was in front of the box. Aircraft data tags, which provided aircraft callsign, altitude, and speed information, could be displayed at any time. When spacing was active, these tags also displayed the spacing status in seconds late (e.g., 22L) or early (e.g., 17E).

Figure 2. Cockpit Situation Display (CSD)

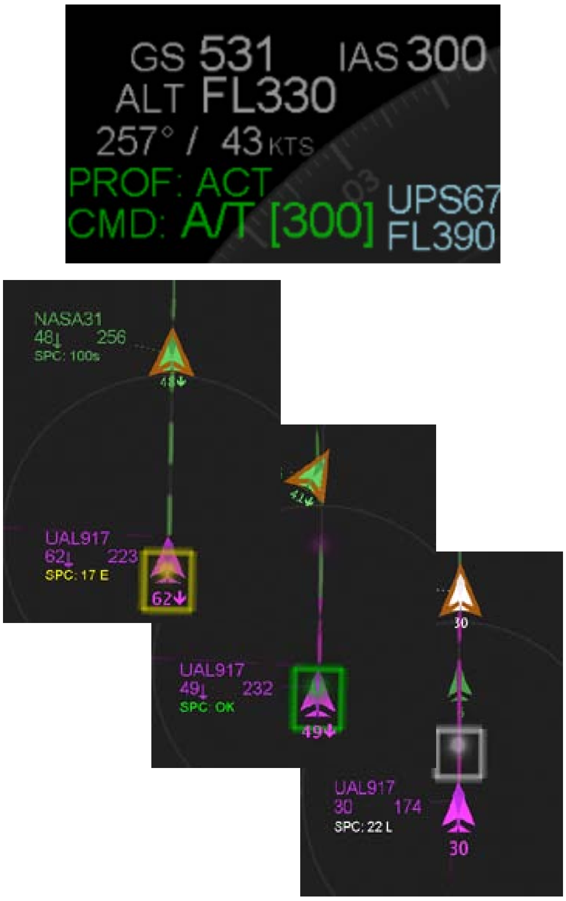


Figure 3. CSD Spacing Status and Command Displays

Once active, the spacing automation recommended speeds that would gradually meet the target spacing interval. The active status of the spacing automation, and the recommended speeds, were shown in the upper left hand corner of the CSD (Figure 3, upper panel shows enlarged views of this part of the CSD). In the Manual Speed Control conditions, these speeds needed to be entered manually. In the Automatic Speed Control conditions, these speeds could be entered automatically, although the pilot could manually override this guidance in the Pilot discretion condition. For example, pilots might want to overrule the recommended speeds if a path stretch to avoid weather was large and the pilot thought the automation was not aggressive enough in making up the delay.

The CSD also included an integrated trial planner, called the Route Assessment Tool (RAT). This tool allowed pilots to "grab" the current route and design new flight paths by stretching the route around weather. Automated conflict alerting algorithms provided visual alerts when proposed routes created traffic conflicts. The RAT also provided feedback on how much delay the reroute generated. The CSD was integrated with the FMS allowing the pilot to execute the new route from the CSD.

Design and Procedure

All pilots flew together in an airspace managed by confederate air traffic controllers. Additional air traffic was flown by confederate "pseudo-pilots," to bring the total traffic load up to about 1.5 times current day traffic. A 2 (Pilot Instruction: Follow Speed Command, Pilot Discretion) x 2 (Speed Control: Automated, Manual) x 3 (En Route Weather: None, Dense Convection, Sparse Convection) fully within subjects factorial design was used. Pilots flew twelve 90-minute trials over three consecutive days. In each trial, two pilots flew using each combination of Pilot Instruction and Speed control.

Prior to experimental trials, pilots received an introductory briefing and in-class training on procedures and tool use during the first day. This was followed by three practice runs. Experimental runs took three days and a fourth day was scheduled for make-up runs. Pilots were debriefed at the end of each day.

While spacing was engaged, the automation recommended speed values were shown in the upper left corner of the CSD. In the Manual Speed conditions pilots had to manually adjust their speeds, while in the Automated Speed conditions the spacing speed commands were coupled to the autopilot so speeds in the autopilot condition were automatically updated (although pilots could manually override these speeds).

In the "Follow Speed Command" conditions pilots were told to faithfully follow the recommended guidance in the Manual condition, and to leave the speed coupled to the autopilot in the Automated. In Pilot Discretion conditions, the pilots could vary from guidance as they saw fit in either the automated or manual conditions. In all conditions if specific tolerance boundaries were breached (e.g., excessive spacing errors, excessive lateral or vertical deviations of Ownship or lead aircraft from the profile descent), the spacing automation would disengage.

Scenarios were built to simulate arrival operations into SDF along the CBSKT 1 arrival (Figure 4). The scenarios began with the experimental aircraft en route, with weather, when present, located between the aircraft and their tops of descent. Spacing clearances were issued and executed prior to deviation for weather so that the pilot could receive feedback regarding the amount of delay caused by their weather maneuver. After deviating for weather (when weather was present) the aircraft merged into a single stream at PRINC, which was located on their CDAs about approximately 40 nm past their tops of descents. After this the pilots followed their lead down the arrival stream through the TRACON meter fix at CBSKT, on to the final approach fix at CHRCL, for a final northern approach into runway 17 right. The trial ended when pilots arrived at the airport. Depending on the location of the pilot's aircraft in the arrival stream, pilots flew for a maximum of 90 minutes.

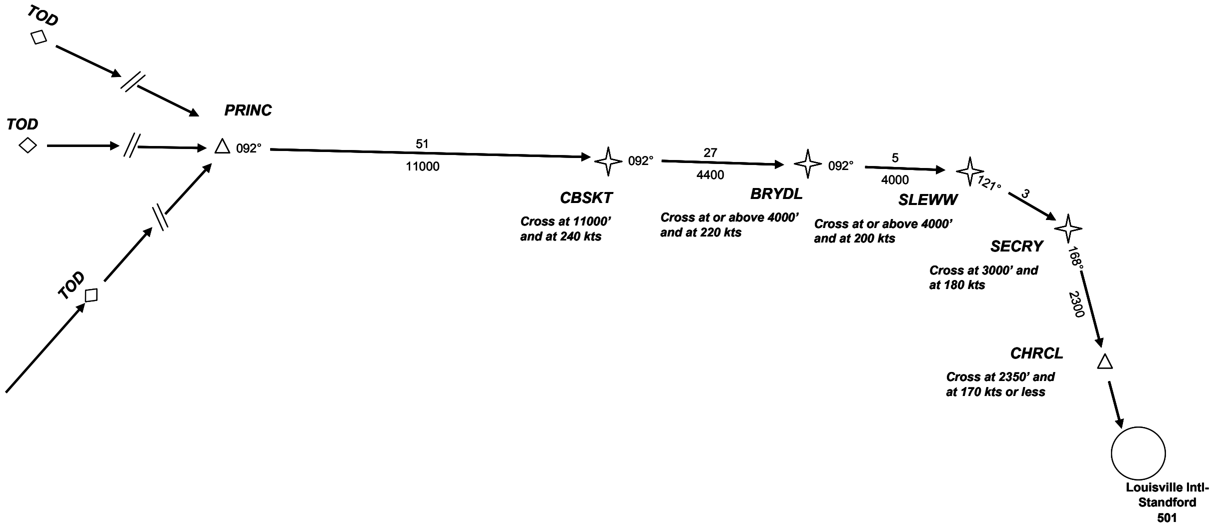


Figure 4. CBSKT 1 Arrival with PRINC Merge Point

Subjective Measures

Two post-trial subjective measures of CDA workload, and one measure of perceived compliance with speed commands, were gathered. Specifically, the ratings were as follows: Overall CDA workload: "Please rate your overall workload associated with the CDA." Peak CDA workload: "Please rate your peak workload associated with the CDA." Compliance rating: "During spacing, to what extent did you base your speed on the spacing algorithm's recommended speed? (Versus other information such as the displayed time error or the trend box.)" Pilots reported workload using a Likert-like scale, with 1 signifying "Low" and 5 signifying "High." For the compliance rating, pilots reported on a scale with 1 signifying "Not at all" and 5 signifying "Entirely."

Results

Analysis of Performance Measures

The main performance dependent variable of interest was absolute spacing error at the final approach fix. This error was determined by calculating the unsigned difference between the target spacing interval assigned at the beginning of the simulation and the time-in-trail (observed spacing interval) at the final approach fix. In addition, the observed times-in-trail were also examined without respect to the assigned spacing. This simply showed the mean spacing (time-in-trail) achieved. In addition to the performance at the final approach fix, times-in-trail at the merge point, PRINC, were assessed in order to determine if the weather disturbances had the expected impact on the intervals in the CDA.

Prior to our analyses we found that, on one trial, a pilot failed to fly the standard approach. Data from this flight and those aircraft following it were not analyzed for this trial, resulting in the loss of four data points. Where needed, for purposes of statistical analyses, we replaced these values with the means from the design cells in which they occurred.

Figure 5 shows the histograms of the times-in-trail for the remaining 92 flights at PRINC for each of the three weather conditions. It clearly indicates that deviating around weather had the expected impact. Specifically, the intervals for the no weather condition clustered around 118 seconds, while the intervals for the dense and sparse weather conditions, while having a mode at 118 seconds, spread out markedly toward higher values. The 118 s value was initially surprising because we were expecting a value closer to the 105 second assigned spacing value. A closer examination of this finding revealed that our implementation of the ASTAR algorithm had both a 105 second spacing parameter, and a requirement to keep 5 nm minimum in trail separation. This separation requirement, in turn, required a 128.5 second separation at the final approach fix due to a 140 kt profile speed at that fix (i.e., it takes 128.5 seconds to travel 5 nm at 140 kts). In such a situation the algorithm defaults to the conservative spacing requirement, 128.5 seconds in this case. So, while the aircraft were started out en route with an approximate 105 second in trail separation, the algorithm began immediately lengthening this interval. By the time the aircraft reached the merge point this was the reason, at least in part, that the separation had grown to 118 seconds. However, as noted in the companion paper to this report [11], strategic actions by the controller are also likely to have influenced this growth, especially for the Dense and Sparse weather conditions.

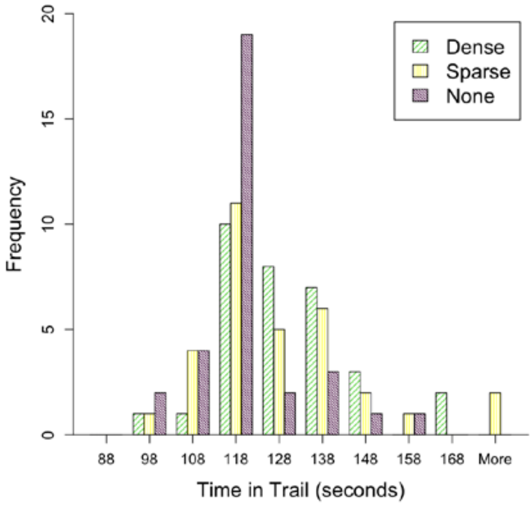


Figure 5. Times-in-Trail at PRINC Merge Point

A histogram of the times-in-trail at the final approach fix (CHRCL) for each of the 92 pilot-trials in the study is shown in Figure 6. The spacing target (128.6 seconds) is indicated by a vertical line. One outlier is apparent in Figure 6; the time in trail for this flight was 250 seconds (111 seconds, late) more than twice the error of the second worst flight which had a time-in-trail of 78 (51 seconds early).

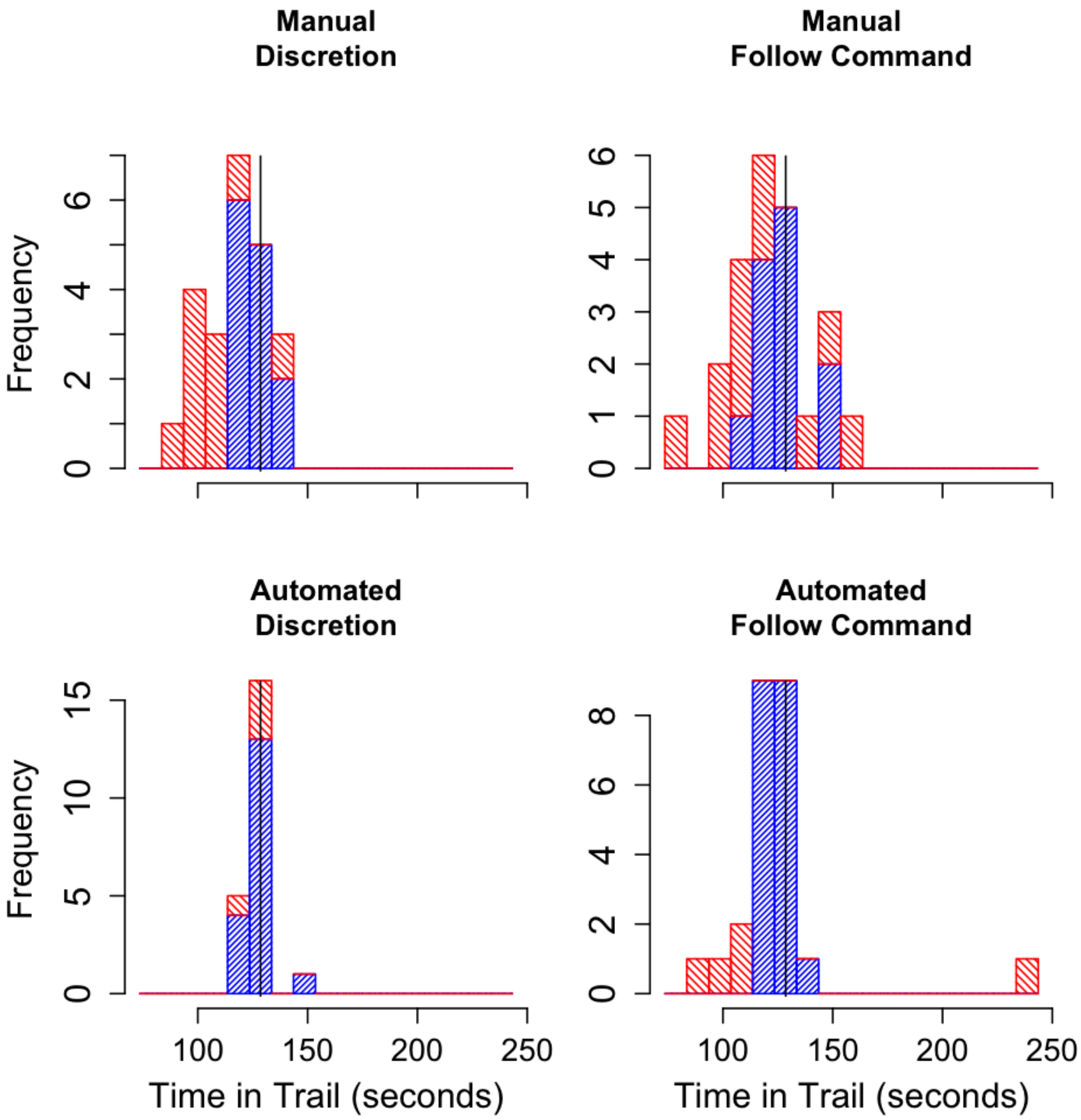


Figure 6. Times-in-Trail at CHCRL Final Approach Fix

Excluding the outlier, unsigned spacing error data from the remaining 91 flights were submitted to a 2 (Pilot Instruction) x 2 (Speed Control) x 3 (Weather) within subjects ANOVA, with pilots as the random factor. There was a significant main effect of Speed Control, $F(1, 7) = 9.2$, $p < .05$, with more aircraft in the Automated Speed condition arriving at the final approach fix close to the assigned interval (128.6 seconds) than in the Manual Speed condition. This effect can easily be seen in the histograms shown in Figure 6. No other effects approached significance.

Why did pilots who were manually inputting speeds to the autopilot have larger spacing errors than those for whom this was done automatically? In many cases it appears that the spacing algorithm became inactive prior to reaching the final approach fix (ceased generating guidance). These are shown in red in Figure 6, while the blue denotes pilot-trials where the algorithm remained active. This happens when the spacing algorithm ‘decided’ that it can no longer achieve the desired interval at the final approach fix, or if it detects that Ownship or the lead were no longer following the route in Ownship’s FMS. Figure 7 shows the median speed and altitude performance at each waypoint during the descent. Flights for which the spacing algorithm remained active at the final approach fix are shown with the blue dotted line, while those where the algorithm was inactive are coded with the red solid line. The solid magenta line denotes the profile speeds and altitudes set in the FMS. Two aspects are immediately apparent. First, flights in the Automated speed control condition were far more likely to remain active than those in the Manual condition. Twenty-one of the 46 flights in the Manual condition became inactive while only nine of the 46 flights in the Automated condition became inactive. This difference was significant ($\chi^2(1) = 7.12$, $p < .01$). Second, much of the difference between the Manual and Automatic speed control conditions can be ascribed to those flights on which spacing did not remain active.

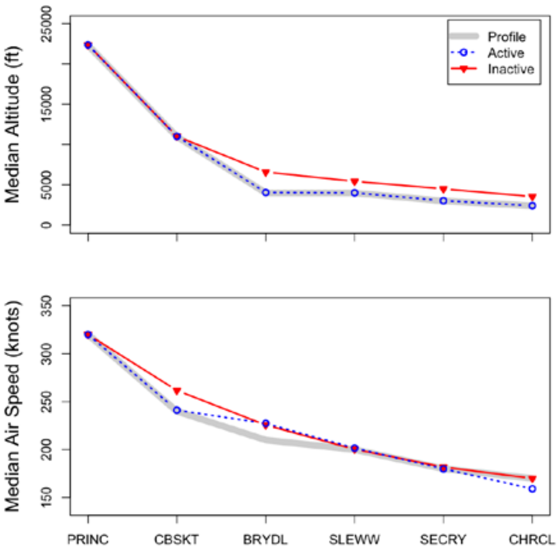


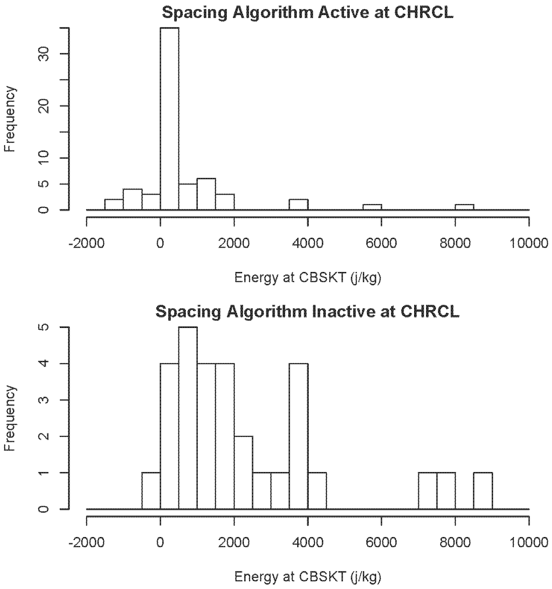
Figure 7. Altitude and Airspeed during Descent

Ideally, planes should maintain the “profile” speeds and altitudes stored in the FMS. Being too high or too fast at any point on the descent can pose problems. Energy management requires the use of flaps and drag in order to carefully “bleed off” energy, i.e., altitude and speed. An unbalanced strategy will not sufficiently take into account that kinetic energy lost due to deceleration tends to transfer to potential energy, i.e., altitude. Figure 7 shows this happened between CBSKT and BRYDL.

At CBSKT only seven flights failed to meet the 11,000 ft altitude restriction, but 33 failed to meet the recommended 240 (±10) knots speed restriction. Spacing was inactive at the final approach fix (CHRCL) for 57% of those failing to meet the restriction in both cases. Clearly speed generated the most problems, and 24 of these 33 cases were in the Manual Speed condition. These fast aircraft did manage to return to profile speed, but their excess energy doomed them to remain high from BRYDL onwards.

Figure 8 supports this reasoning, using a histogram to compare the excess energy at CBSKT of the flights whose spacing was inactive by the time they reached CHRCL with the excess energy of the flights whose spacing remained active. Excess energy, relative to the profile CDA was calculated using the equation:

$$\text{Energy} = \tfrac{1}{2}m(v_{ref} + \Delta v)^2 + mg(h_{ref} + \Delta h)$$


Spacing Algorithm Active at CHRCL

Spacing Algorithm Inactive at CHRCL

Figure 8. Excess Energy at CBSKT

Here $\underline{m}$, is the aircraft mass, (assumed to be the same for all aircraft), $\underline{g}$ is gravity, $\underline{v_{ref}}$ and $\underline{h_{ref}}$ are profile velocity and altitude, and $\underline{\Delta v}$ and $\underline{\Delta h}$ are the deviations from the profile. The equation was then solved for the excess energy due to these deviation components. The flights for which spacing was inactive at CHRCL were much more likely to have an energy management problem, with 67% of them having more than 500 joules excess energy at CBSKT for each kilo the plane weighed. Only 29% of the flights that were still active at CHRCL had similar excess energy. An examination of the usage of the speed brake between PRINC and BRYDL (Figure 9) also confirmed the excess energy problem. Active aircraft (shown in blue) had a much higher usage of speed brakes than inactive aircraft (shown in red), indicating that the inactive aircraft pilots were not aware that the aircraft energy was high; whereas the active aircraft pilots were more proactive in monitoring the energy state and made adjustments accordingly.

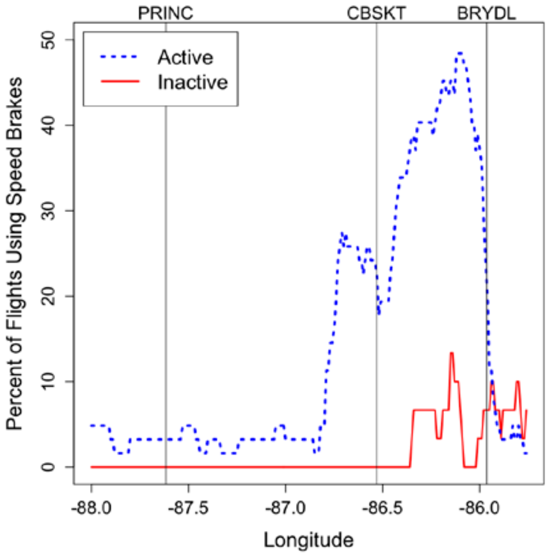


Figure 9. Speed Brake Usage Between PRINC and BRYDL

Thus it appears that excess energy was the likely reason for aircraft not being able to fly their profiles, and this in turn caused the spacing algorithm to go inactive. For flights off profile at CBSKT, the likelihood of the spacing automation becoming inactive is about the same for the flights with the recommended speed coupled to the autothrottle (8/13) and for the manually coupled flights (18/27). Furthermore, this excess energy was most prevalent when the pilots were required to manually enter the speeds.

To further understand how the manual entry of speed commands led to poorer energy management, we examined how closely the pilots followed the automated speed guidance. We did this by sampling the ASTAR speed guidance and the commanded speed at two second intervals, subtracting the two to get a speed error measure, and finally compiling these into histograms for each of the four conditions (Figure 10). From this it is clear that the pilots using the manual inputs did not closely follow the guidance, and this is the likely cause of the poor energy management. It is worth noting that there is only very minor evidence that giving to pilots the discretion to override suggested speeds led them to do so.

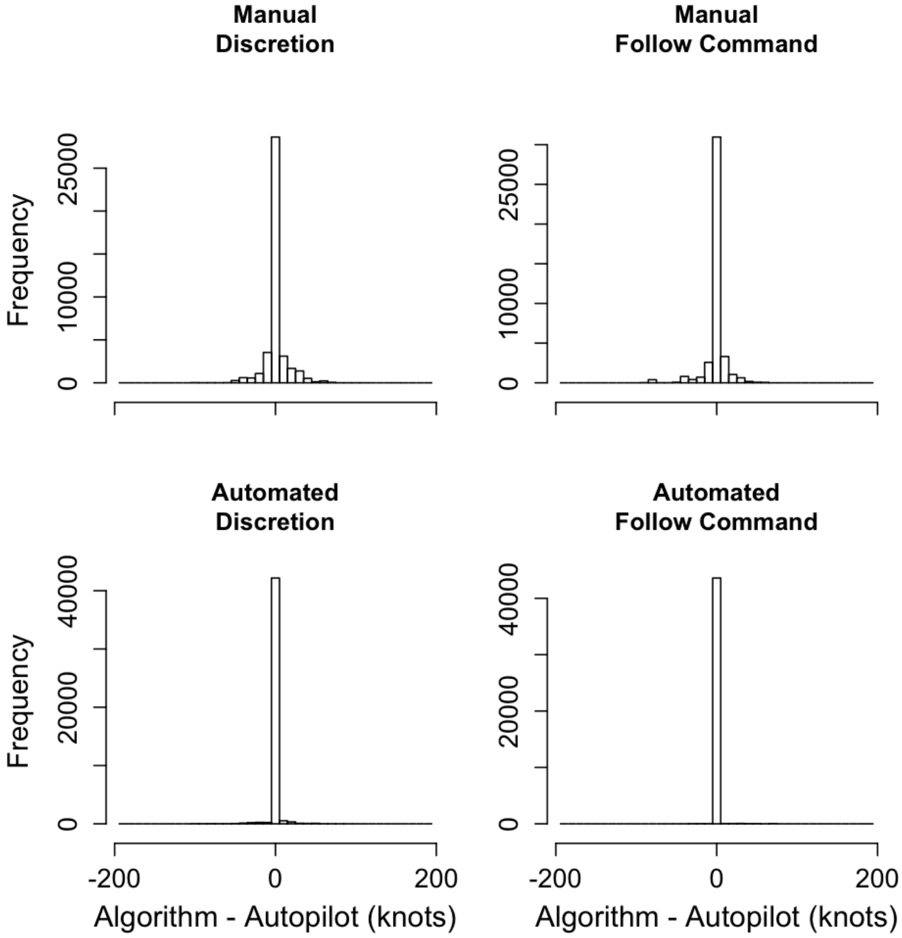


Figure 10. Commanded Speed Error

Finally, the times-in-trail data at the final approach fix were subjected to a similar 2 (Pilot Instruction) x 2 (Speed Control) x 3 (Weather) within subjects ANOVA. This yielded a significant Pilot Instruction x Automation interaction ($F(1, 7) = 6.7$, $p < .05$). Figure 11 shows that allowing pilots' to insert their own judgment leads to a mean spacing interval that is closer to the target (128.5 seconds) when automated speed control is available, but somewhat worse performance when pilots must manually enter the speeds. Why this should be the case is not clear, but this finding suggests that issues associated with manual entry may be masking some benefits of allowing the pilots to exercise their judgment.

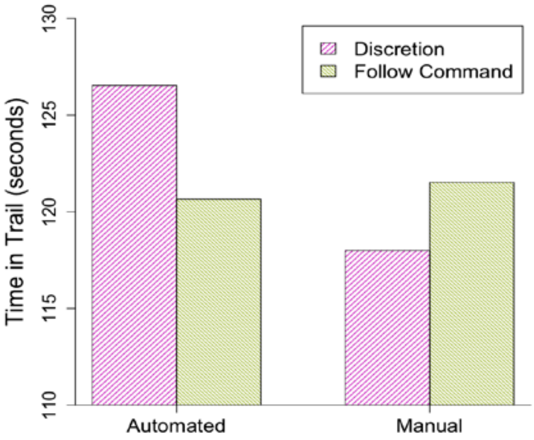


Figure 11. Time-in-Trail at CHCRL Final Approach Fix

Analyses of Subjective Measures

The overall means for the CDA workload ratings were approximately 2, suggesting that the pilots had a relatively low workload throughout the CDA.

Three-way (Weather x Pilot Instruction x Speed Control) ANOVAs were conducted on the workload and compliance ratings. There were significant main effects of Speed Control for both overall CDA workload $F(1,7) = 10.65$, $p = .01$, and for peak CDA workload, $F(1,7) = 12.78$, $p = .01$ (Figure 12). There was also a significant main effect of Weather for peak CDA workload, $F(1,7) = 9.26$, $p = .003$, and a marginally significant effect for overall CDA workload, $F(1,7) = 2.88$, $p = .09$, (Figure 13). There were no other significant effects for the subjective measures.

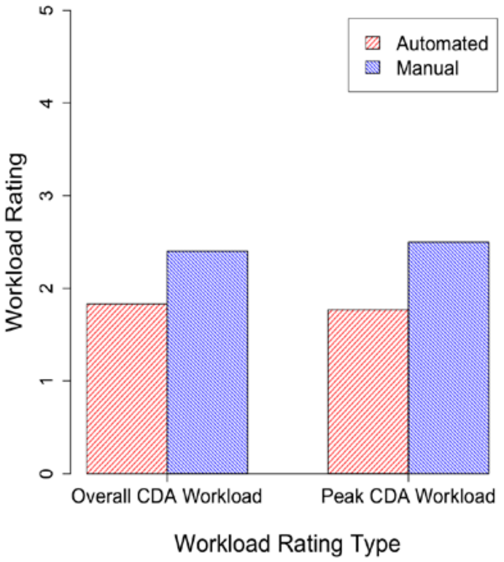


Figure 12. Workload as a Function of Speed Control

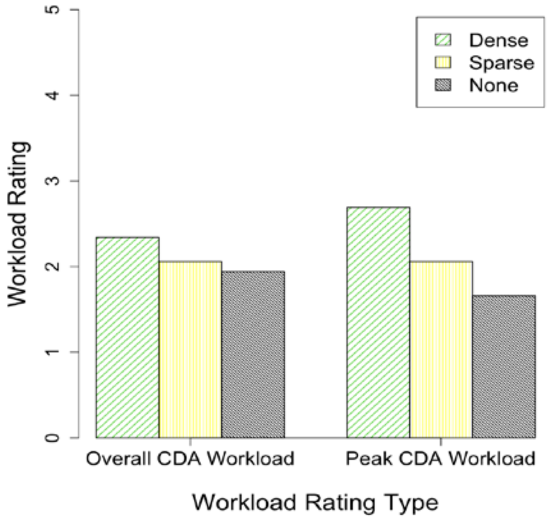


Figure 13. Workload as a Function of Weather

It is not surprising to find greater workload for manual speed inputs. However, the lack of any significant effect in the analyses of the compliance ratings is somewhat peculiar. We might have expected them to reflect the effects of the Pilot Instruction variable shown in Figure 11. That is, if pilots show an effect of the Instruction variable then they are, nominally, showing that they were less compliant with the automated speed guidance in some situations. More surprising, however, is that despite frequent failures to match autopilot speed to the automated speed guidance in the non-discretionary Manual Speed Control conditions, Pilots did not rate their compliance lower in those conditions.

Discussion

Overall, the results paint an incomplete, if not somewhat contradictory, picture. First, the clearest finding was that pilots encountered energy management problems when required to directly and continuously manage the speeds in the combined CDA/Interval management operation. This was primarily shown in the analysis of the unsigned error. A second more complex finding showed that allowing pilot to exercise discretion to overrule the speed guidance resulted in mean spacing intervals that were closer to the target interval when automated speed control was available; but this was absent, and perhaps reversed when manual speed control was required.

An examination of Figures 6 and 10 shows that the deleterious effects of having to manually manage the speed must be far more pronounced than any positive or negative effects due to allowing pilots to have discretion over the speeds. The analysis of the spacing intervals at the final approach fix showed a large impact of Speed Control, but no statistically significant effect of the Pilot Instruction variable. However, an examination of Figure 6 does show some improvement when pilots are given discretion, particularly in the automated condition. Figure 10 shows that requiring manual speed inputs has a much greater impact on spacing intervals at the final approach fix. In Figure 10, the size of the speed error bins is 20 knots. Under the Automated conditions only a tiny number of samples fell outside the central (0 ± 10) bin, although those samples were in the condition that allowed for pilot discretion. Therefore, the changes in spacing interval performance reflected in Figure 11 must have been due to relatively minor tweaks to recommended speeds. On the other hand the variation in speed error under the Manual conditions was very pronounced.

The degree to which requiring the manual entry of speed commands had a deleterious effect was surprising. There are several possible reasons for this finding, but here we will only discuss three. First, pilots may have had trouble entering commands using the provided speed control interface. We used a software emulation of a knob control and, although trained on its use, pilots may have found it awkward to use a computer mouse to control the knob rather than to use their hands to turn a knob. It is hard to know if this was the case, since the pilots did not report this, nor was this observed by the researchers running the simulation, and the reports on other human-in-the-loop research on this system did not note such problems [10]. However, since the mouse input was the only input device available, the pilots may not have complained about input method; nevertheless, it remains a possible explanation. On the other hand, once pilots are continuously in the loop they may tend to deviate from the automated speed guidance regardless of instruction; automated entry of speeds may prevent pilots from making ill-considered adjustments. Finally, and the explanation we would most likely consider for further exploration, is that the pilots may not have been provided with all the necessary information to adequately deal with the combined workload associated with monitoring/managing airplane energy, and with monitoring the recommended speeds and entering them into the autopilot. This could account for the observed delays in the timely deploying of speed brake, and/or the non-compliant entry of recommended speed adjustments. If pilots in the manual condition were insufficiently aware of their energy state, they could have easily slipped into trouble due to the complex nature of achieving three inter-related goals: 1) maintaining the desired spacing interval; 2) meeting altitude and speed restrictions; and 3) managing the aircraft energy. Our findings showed that the interval management system examined performs better at higher levels of automation where there is low human intervention. Such a requirement can be achieved in two ways. First, it can be achieved by training the pilots to limit their intervention because they cannot understand how the system is working. Second, a more robust implementation would require additional research that seeks to make the operation of the automation more transparent to pilots and provides them with the necessary information so that their expertise can be exploited to achieve the three inter-related goals. Specifically, the interval management automation can be augmented with additional information for energy management to tell the pilot whether the aircraft energy is low or high relative to the baseline profile, and the margin from the tolerance boundaries of the spacing automation before it would disengage. Providing information pertaining to energy management has been explored in a number of research projects, with solutions ranging from near-term to far-term implementation.

In addition to known energy management enhancements (e.g., green energy arcs), other possibilities exist for near-term implementation. For example, it has been shown in simulation studies [14] that a non-automated cueing system consisting of altitude/speed checkpoints ("gates") and a recommended flap schedule along the profile in the approach chart, can provide pilots with feedback on the energy state of the aircraft, and thereby enable them to fly CDA profiles consistently and improve the predictability of the aircraft's trajectory and separation. A variation of the gates cueing system was tested in a CDA flight demonstration test [15] in which recommended speed, altitude, and flap settings were provided at specific waypoints on the approach chart in order to provide pilots with information to make adjustment to the energy of the aircraft. Other far-term, more automated solutions have also been proposed, such as the use of an electronic flap deployment system to display flap/gear cues in the speed tape of the primary flight director [16], or the use of an energy indicator in conjunction with flap and gear annunciations as guidance events to help pilots determine when to extend the flap and gear [17]. Whichever supplemental information pertaining to energy management is adopted to complement the interval space automation, it should be a goal to make the automation more transparent by either aligning the automation's logic and rationale with the strategies/mental models of the pilots, or by making the model behind the automated logic easily and simply accessible. While this is a challenge, it must be done in such a way that the value of human adaptability and flexibility in response to perturbations (e.g., due atmospheric uncertainties or aircraft non-conformance) can be captured and utilized.

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