Automated Spacing Support Tools for Interval Management Operations during Continuous Descent Approaches

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In this study, pilots were asked to achieve a specific time in trail while flying an arrival into Louisville International airport. Weather shortly before the start of the descent added variability to the initial intervals. A spacing tool calculated airspeeds intended to achieve the desired time in trail at the final approach fix. Pilots were exposed to four experimental conditions which varied how strictly the pilots were told to follow these speeds and whether speeds had to be entered into the autopilot manually. Giving the pilots more discretion had little effect on the final spacing interval. However, pilots required to enter speeds into the autopilot manually did not effectively manage their airplane's energy resulting in less accurate performance. While these results may not always generalize to alternative spacing implementations, one should not assume pilots manually closing the loop on automated commands can perform as well as a fully automated system.

INTRODUCTION

Next Generation Air Traffic Management (NextGen), is an initiative spanning multiple federal government agencies that seeks to modernize how air traffic is handled and increase the overall efficiency and safety of the system (Joint Planning and Development Office, JPDO, 2010). The JPDO recognizes that achieving increased safety, efficiency, and capacity goals for the NAS by 2025 will require more support from automation. In response, the FAA and NASA are examining a variety of advanced flight deck automation tools including tools to support approach and arrival operations into and through congested terminal airspace (Prevot et al., 2004; Prevot et al., 2005; Barmore, 2006).

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 approach and arrivals (CDAs). CDAs are a new type of descent designed to reduce noise, emissions, and fuel use by having aircraft descend continuously rather than in a series of steps.

In proposed operations, pilots oversee the spacing between their aircraft and the aircraft in front of them while conducting CDAs. Such operations have been alternatively called merging and spacing, or more recently, interval management. Interval management involves the merging and spacing of aircraft as they approach the airport in order to achieve scheduling goals (Federal Aviation Administration, 2009). Merging applies to aircraft that are adjusting to an in-trail position behind an assigned lead aircraft approaching from another stream (Sorensen, 2000). Spacing occurs when aircraft try to achieve, and/or maintain, a specified spatial or temporal distance from an assigned lead aircraft.

Prevot et al. (2007) 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 datalinked from control stations to flight decks; in the ground-based option the controllers had the automation tools to help them determine speed clearances. Pilots using flight deck automation loaded the datalinked spacing intervals and 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 (e.g., Barmore, Abbott, Capron & Baxley, 2008). 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 trial. ASTAR can be contrasted with most other approaches to interval management, such as the one used by Prevot et al. (2005, 2007) which are based on an aircraft attaining and maintaining a spatial 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 an aircraft to 1) arrive at the final-approach-fix at an assigned time in trail and 2) to fly the profile speeds in between these adjustments. See Abbott (2002) for more details on the algorithm.

Computer based fast-time tests have shown that good interval management performance can be achieved with airborne-based ASTAR spacing automation (Barmore et al., 2008), Improved interval management performance was also found when pilots used ASTAR automation to execute aircraft-to-aircraft spacing tasks (Barmore et al., 2005, 2008). 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 (Barmore, 2006). Route modifications can be in response to traffic conflicts or hazardous weather. Further, to date, all simulations have taken steps to insure that the algorithms 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 unavailable to the automation such as that a deviation for weather will be necessary). 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 (the presence of weather).

Current Study

The current study examined the robustness of interval management operations during continuous descent approaches using the ASTAR automation. Of particular interest was how pilots use the ASTAR automation to simultaneously manage spacing and the CDA. Managing both goals can be seen as a difficult energy management task, where the spacing operation, maintaining a continuous descent approach, and the need to meet speed and altitude restrictions along this approach, all depend on speed. 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 (Barmore et al., 2005, 2008). In those studies, however, the evaluations either used computer based evaluations (no human-in-the-loop), or pilots were trained to rigorously and strictly follow automated guidance. The present study compared cases where the strict procedures were relaxed to allow pilots to exercise their own judgment if they thought they knew better than the automation. Two manipulations examined how factors related to human-automation integration would affect spacing performance. 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 the automation would automatically implement automated 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 pilot 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, and as a result, encounter trouble managing the two tasks. No prediction was made for the Speed Control manipulation, but it was included because both modes of operation are under active consideration in NextGen.

In addition to the above manipulations, a *Weather* manipulation examined performance in the presence/absence of weather that had to be avoided. The goal was to generate a disturbance to the initial spacing task by requiring route modifications to get around the weather, and thereby place significant stress on these operations. Since no effects were found for weather, it will not be considered in the rest of this report. Other than the above procedures, the procedures used in the study were similar to those used by Prevot et al. (2007).

Finally, this study used distributed simulation architecture, with pseudopilots located at NASA Ames, California State Universities at Long Beach and Northridge, and at Purdue University. These pseudopilots were confederate pilots whose task was to manage the air traffic populating the airspace around the experimental group. Confederate controllers were located at California State University Long Beach. All participant pilots were tested at NASA Ames.

METHOD

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 provided pilots with an interface that allowed flying their aircraft with tools normally found in current day Boeing 747 aircraft (Prevot, 2002). 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. It is widely assumed that this interface (referred to as "datalink") will replace most voice communications. Pilots were able to manipulate aircraft speed using typical 747 speed controls and displays simulated by MACS.

The CSD (shown in 2D mode in Figure 1) 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 a view of

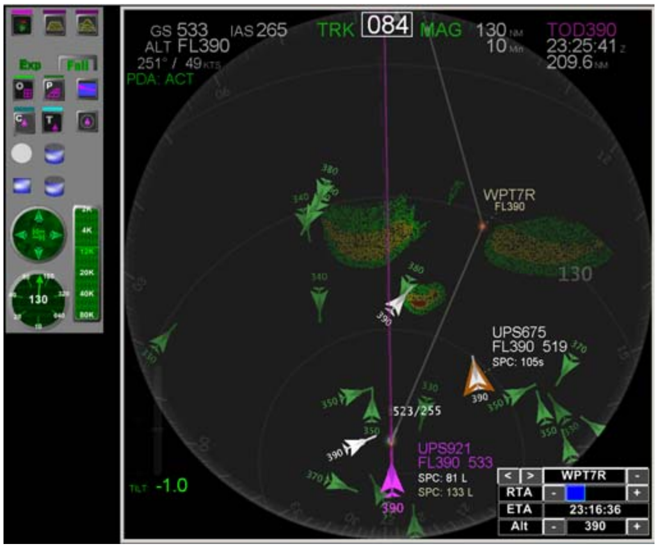

Figure 1. 3D Cockpit Situation Display.

traffic within 160 nm and a simulated airborne weather display with a radar tilt control. With the exception of weather, in this experiment the CSD could display all information in two dimensions (top down or profile), or in three dimensions. Additional details regarding the CSDs capabilities are described in Granada, Dao, Wong, Johnson, and Battiste (2005).

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 2). 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 was behind the box and yellow if ownship was in front of the box. Aircraft datatags, 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).

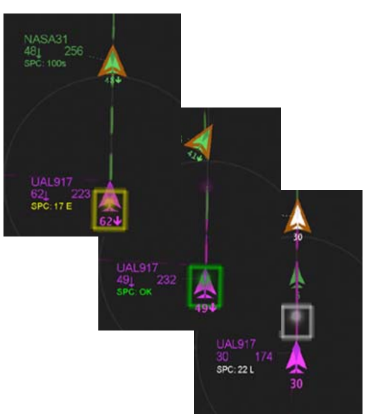

Figure 2. Spacing box shows aircraft spacing status. Yellow indicates “early”. Green indicates “on-time”. White indicates “late”.

Once active the spacing automation recommended speeds that would gradually meet the target spacing interval. In the Manual Speed Control conditions, these speeds needed to be entered manually. In the Automatic Speed Control conditions, these speeds would be entered automatically, although the pilot could manually override this guidance in the Pilot discretion condition. For example, pilots might want to overrule the commanded 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 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 (Instruction: Follow Speed Command, Pilot Discretion) x 2 (Speed Control: Automated, Manual) 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 Instruction and Speed control.

Prior to experimental trials pilots received an introductory briefing and in-class training on procedures and tool use. 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 commanded 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 initially coupled to the autopilot so speeds in the autopilot were automatically updated. In the Follow Speed Command conditions pilots were told to faithfully follow the commanded 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 the certain tolerance boundaries were exceeded, the spacing automation would disengage.

Scenarios were built to simulate arrival operations into Louisville Kentucky Airport (SDF). 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) pilots followed their lead down the arrival stream for a 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.

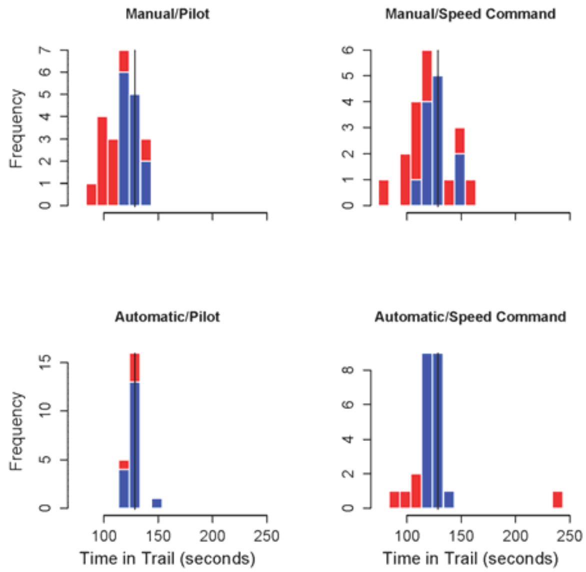

Figure 3. Time-in-trail at the final approach fix for each of the 92 pilot-trials in the study. The spacing target (128.6 seconds) is indicated by a vertical line. Red: pilot-trials on which the spacing became inactive. Blue: pilot-trials on which the spacing algorithm remained active.

RESULTS

The main dependent variable of interest was spacing error at the final approach fix. Spacing error was determined by calculating the difference between the target spacing interval assigned at the beginning of the simulation and the observed spacing interval at the final approach fix.

On one trial a pilot failed to fly the standard approach. Data from this flight and those following it were not analyzed for this trial, resulting in the loss of four data points. Time-in-trail for the remaining 92 flights is shown in Figure 3. One outlier is apparent in Figure 3; 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).

Spacing error data from the remaining 91 flights, excluding the outlier, were subjected to a 2 (Instruction) x 2 (Speed Control) within subjects ANOVA, with pilots as the random factor. There was a significant main effect of Speed Control, $F(1, 7) = 9.2$, $p < .05$. This effect can easily be seen in the histograms shown in Figure 3. 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 failed. The spacing algorithm no longer attempts to achieve the appropriate spacing when the plane fails to meet certain conditions. In Figure 3, flights for which the spacing algorithm remained active at the final approach fix are coded in blue, while those where it did not are coded in red. 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

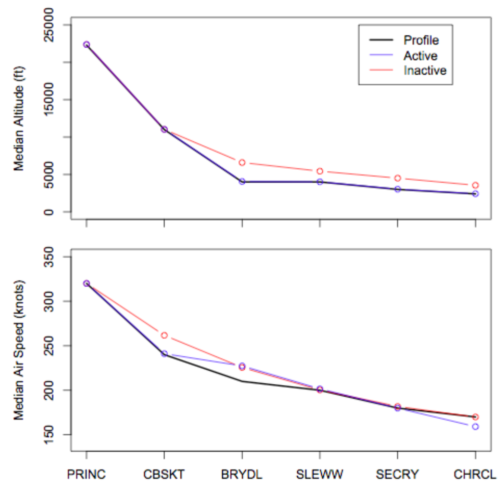

Figure 4. Median altitude and air speed at each waypoint on the descent. Profile: The target altitude and airspeed set in the FMS. Active: Spacing algorithm remained active until the final approach fix. Inactive: Spacing algorithm was inactive at the final approach fix.

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.

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 4 shows this happened between CBSKT and BRYDL. At CBSKT most flights were meeting the 11,000 ft crossing restriction. Only seven flights failed to meet this restriction, four in the automated and three in the manual speed control conditions. Of these seven, four eventually had their spacing fail (two in the automated condition and two in the manual). However, many flights were faster than profile and had their spacing inactive by the time they reached CHRCL. A full 33 of the 92 flights were above the profile speed of 240 (±10) knots. Nine of these flights were in the automated condition (of which four went on to be inactive at CHRCL) and 24 were in the manual condition (of which 15 went on to be inactive at CHRCL). These aircraft brought their speed down to match the speed of the group whose spacing stayed active, but excess energy doomed them to remain high, from BRYDL on.

Finally, Figure 5 supports this reasoning, showing how excess energy was associated with the group whose spacing was inactive at CHRCL. Excess energy, relative to the profile CDA was calculated using the equation

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

Here m, is the aircraft mass, (assumed to be the same for all aircraft), g is the force of gravity, v_{ref} and h_{ref} are profile velocity and altitude, and Δv and Δh 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/kilo excess energy at CBSKT, Only 29% of the flights that were still active at CHRCL had similar excess energy.

So 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 commanded 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.

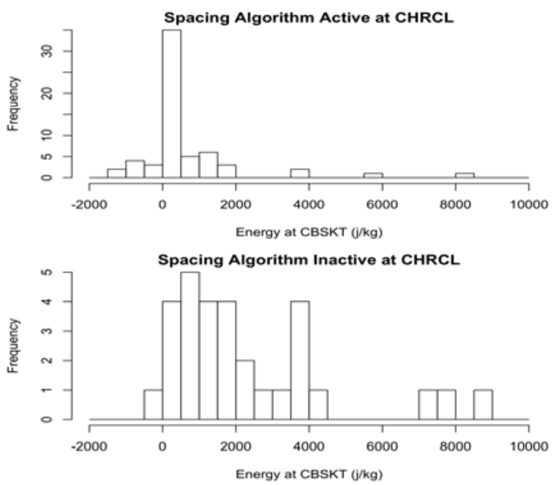

Figure 5. Excess energy at CBSKT as a function of whether spacing was active at the final approach fix (CHRCL).

CONCLUSIONS

The hypothesis that pilots would encounter energy management problems when allowed to intervene in the combined CDA/Interval management operation was partially confirmed. The surprising finding was that these problems were a function of whether the pilots had to enter speed commands manually, and not as a result of whether they were given discretion to override/augment the automated speed commands. There are a couple possible reasons for this finding. First, once the pilots are in the loop they may tend to deviate from the automated speed commands regardless of instruction. Alternatively, the pilot may not have been able to adequately deal with the combined workload associated with monitoring/managing airplane energy, and with monitoring the commanded speeds and entering them into the autopilot. This could have resulted in delays in the timely deploying of speed breaks, and/or the entry of needed speed adjustments. Whatever the cause, pilots in the manual condition appear to have trouble due to the complex nature of the energy management task. Thus, our findings show that current interval management systems perform 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 never intervene because they cannot understand how the system is working. A more robust implementation however, would seek to make the operation of the automation more transparent. Given the automation's complexity this may be a challenge, but it should be a goal to not introduce more non-transparent automation, such as the present day FMS, onto the flight deck.

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