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Pilot-Performed In-Trail Spacing and Merging: An Experimental Study

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Responsibility for the guidance of aircraft in the National Airspace System is currently given largely to the air traffic controller. This study investigated the benefits of having pilots more involved in guidance during two representative air traffic management operations: maintaining in-trail separation and arrival sequencing. This included 12 airline pilots flying arrival routes in a part-task, medium-fidelity simulator, during which they were responsible for attaining and maintaining a commanded relative position within the traffic flow. A variety of cockpit displays of traffic information and procedures were tested, and the pilots' performance was tracked during both nominal and off-nominal traffic situations. Results provide preliminary evidence of the benefit of pilot involvement in the guidance component of these operations. Suggestions are given for modifications to cockpit avionics systems. The need for established air traffic control procedures to provide foreknowledge to the pilots and a structure within which pilots can interact is also highlighted, illustrating that improvements to aircraft guidance within the National Airspace System may benefit from both technical and procedural changes.

Introduction

ALTHOUGH control over aircraft attitude is maintained by the pilot or autopilot, responsibility for guidance and route planning is, in accordance with the federal aviation regulations, given largely to the air traffic controller when the aircraft is in the National Airspace System (NAS). Except during a state of emergency, a pilot in controlled airspace is required to comply with air traffic controller instructions (or constraints) on speed, heading, altitude, vertical speed, and future route. In generating these commands, the controller has several objectives. The most obvious objective is guaranteeing safe aircraft separation. When airspace is congested, effective air traffic management (ATM) also becomes an important objective, as measured by the controller's ability to organize aircraft into traffic flows that take better advantage of airspace capacity while reducing inefficient maneuvers and unnecessary delays.

Meeting this ATM objective requires the controller to perform several tasks. First, it must be decided where the traffic flows should go, which aircraft should be streamed into which flow, and at what distance aircraft should be spaced in-trail within a flow. These high-level concerns are not typically communicated to the pilot; instead, the controller has the second task of translating them into low-level steering commands for the pilot. This second task adds to controller workload and limits pilots' understanding of the traffic flow and of the controller's intentions.

Current methods of air traffic control are generally considered insufficient for the future demands of air travel and for desired safety levels. At an extreme, it has been proposed that responsibility both for ATM and for aircraft separation be transferred to the flight deck (and, to some extent, to airline operating centers). Nearer-term changes are also being widely examined, such as methods of improving controller's ATM performance through automated aids and through the dynamic resectoring of airspace or changes in the routes taken by traffic flows in response to capacity demands and weather.[1–5] Most of these efforts, however, have focused on the development of new technologies and/or substantial changes in the roles of the controller and pilot; as such, they are not intended for immediate widespread deployment.

Significant near-term benefit may be found in the application of currently available technology and moderate changes in personnel roles. This paper focuses on involving pilots to a greater extent in guidance, while keeping the controller in charge of ATM. Specifically, the controller remains responsible for making the traffic flow decisions; the change is that the controller can then communicate these decisions at a higher level to the pilot (e.g., "Follow BA123 with 8 n miles in-trail") rather than requiring the controller to calculate and communicate lower-level guidance commands. This study examined two operations pilots may perform: in-trail spacing, in which the pilot is asked to follow another aircraft in the traffic stream at a specified distance, and merging, in which the pilot is asked to help create a space for another aircraft to join (merge into) the traffic stream. These operations require greater involvement by the pilot in the traffic flow; rather than just following guidance commands, the pilot is now called on to develop a strategy to maintain position within the traffic flow.

This comparatively small change in personnel roles may have several benefits.[6,7] First, it may increase ATM efficiency by allowing closer in-trail spacing between aircraft and by improving the consistency with which these spacings are maintained because pilots will be assisting the controller more directly. Second, it may improve safety by providing more direct communication between pilots and controllers about the traffic flow, enabling pilots to join in the monitoring of the actions of other aircraft and obviating the practice of pilots attempting to infer controller intentions from isolated low-level commands. Finally, it may reduce controller workload and congestion on voice communication frequencies by reducing the number of commands the controller needs to broadcast to maintain a stable traffic flow, while presumably not increasing pilot workload unreasonably.

These operations may be enabled by the cockpit display of traffic information (CDTI). Basic CDTI are already installed in commercial (and some military transport) aircraft in the form of the traffic situation display component of the traffic alert and collision avoidance system (TCAS). Pilots have already reported using this display to infer and maintain their place within the traffic flow.[8] Previous studies have also found potential benefits of using basic CDTI to perform in-trail spacing.[9–12] Improved CDTI are being investigated[13,14] and near-term implementation is realistic once benefits are demonstrated. Questions still remain, however, as to the amount of information CDTI will need to provide pilots for in-trail spacing and merging operations.

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However, CDTI is not the only source of information available to pilots. Whereas procedures are often thought of as a list of actions,[15] air traffic control procedures also create a structure within airspace that provides a basis for pilots to infer other aircraft behavior. These procedures are published in forms that allow the pilot to anticipate and prepare for a wide range of circumstances. For example, standard terminal arrival routes (STARs) are published on STAR charts that highlight the waypoints and altitudes to expect during an arrival to a major airport; some STARs also indicate expected speeds along the route and merging arrival routes.

Procedural information has fundamental differences from that provided by the CDTI. Only a real-time display is capable of persistently presenting real-time traffic information. However, the utility of this real-time information is limited by several factors. First, the display's ability to update its information frequently is not necessarily matched by the pilot's capacity to sample at an equal bandwidth. Second, concerns about display clutter and information overload illustrate the limits of the pilot to perceive and consider a large amount of real-time information, especially during busy phases of flight.

Conversely, procedural information is not descriptive information, that is, it does not represent the world as it is. Instead, it is normative (i.e., it represents the world as it is supposed to be), limiting its assistance in dealing with the off-nominal. Despite this limitation, procedures have compelling benefits: Procedural information can serve as the basis for foreknowledge, expectations, and planning. As such, pilots commonly brief themselves on upcoming procedures such as departures, arrivals, and approaches before they are flown. From this viewpoint, the role of descriptive information can be simplified from presenting a comprehensive view of the world in an absolute sense (with its commensurate problems with information overload and display clutter), to the comparatively simpler purpose of allowing the pilot to assess whether all is proceeding according to procedure.

The removal or relaxation of procedures in the ATM environment is often an explicit or implicit objective in ATM research and design.[16] However, when their role as a source of information is considered, continued reliance on procedures (in some form) is seen to have benefits. In models of manual control, for example, pilot performance is generally best when the pilot can apply predictive information about the environment to the control and guidance task[17]; within the ATM environment, such predictive information is typically defined by procedures. Likewise, in cognitive models of human control behavior, strategic and tactical control is only possible from the human when he or she has some foreknowledge about the environment; in an unproceduralized, unpredictable environment, the pilot can only be expected to react opportunistically to events as they occur.[18]

In summary, pilot-performed guidance can potentially benefit the safety and efficiency of ATM. However, several questions remain. Is it feasible for pilots to perform these operations? If so, what procedures and cockpit systems will they require? This study examines these questions for the operations in-trail spacing and merging, with specific comparison of different amounts of real-time information presented by CDTI and procedural information presented by STAR charts.

Objectives

One method of pilot-performed guidance asks controllers to determine the in-trail spacing and merging operations needed for efficient ATM, and then for controllers to communicate these desired actions to pilots, leaving the pilots to guide their own aircraft to meet these actions. It is reasonable to hypothesize that conducting these operations in the NAS depends on having a complementary combination of CDTI technology and procedural structure. This study provided a preliminary investigation of two major issues with pilot performed guidance within the NAS: 1) the general ability of pilots to perform in-trail spacing and merging as commanded by the controller, given the pilots' abilities and workload, and 2) the avionics (specifically, CDTI) and procedures required to perform these operations, including interactions between these two sources of information.

Experiment Design

This experiment examined pilot-performed in-trail spacing and merging. The arrival phase of flight was chosen as a test case because it is typically proceduralized by use of a STAR, which consists of a series of waypoints to follow; altitude and speed constraints or expectations, as well as merging arrival routes, may also be stipulated. STARs are published and communicated to pilots by STAR charts.

Experiment Procedure

At the beginning of the experiment, the pilot was taken through a briefing that outlined the experiment and its expectations of the pilot. Following the briefing, the pilot was taken through the first of two training runs. The first training run acclimated the pilot with flying the aircraft through the simulator using the given displays and controls; no controller commands were broadcast, and the traffic density was approximately half that of a normal test arrival. The second training arrival presented the pilot with the usual traffic density of an arrival route and with controller commands. The pilot could repeat any of the training if so desired. The training was completed once the pilot felt comfortable operating the simulator, understood the display and procedure formats, and understood what the pilot was expected to do with regard to performing the ATM operations.

Each pilot then flew seven test runs, with each test run lasting approximately 20 min. To avoid pilot familiarity with a common arrival route, hypothetical scenarios were created following the structure of current STARs. Although each route shared a common underlying structure and was intended to be of the same difficulty, slight differences were made between each to prevent the pilot from relying on rote learning. Following each test run, the pilot was given a set of questions pertaining to that arrival scenario. At the end of all of the runs, the pilot was given another set of questions pertaining to the experiment as a whole. The entire procedure lasted approximately 4 h.

At the start of each test run, an experimenter, acting as an air traffic controller, cleared the pilot for a STAR. The pilot was started approximately 15 n mile in-trail of another aircraft immediately ahead on the arrival route, and the controller immediately issued an in-trail spacing command of 12 n miles through a voice transmission such as, "GT123, maintain 12 n miles in-trail behind QS557." During the run, the controller issued two more in-trail spacing distances (10 and 8 n miles) for the pilot to achieve. The pilot was instructed to vary his aircraft speed to achieve and maintain the commanded spacing. Further down the STAR, the pilot was commanded to merge his aircraft between two aircraft joining the STAR from a separate arrival path on the right or left through a voice transmission such as "GT123, cross behind BI435 at a specified intersection, maintain 4 n miles in-trail behind BI435." After the merge, the pilot was to maintain 4 n miles in-trail behind the aircraft that merged in front. The only commands issued by the controller specified in-trail spacing or merging. The controller did not issue airspeed, altitude, or heading changes.

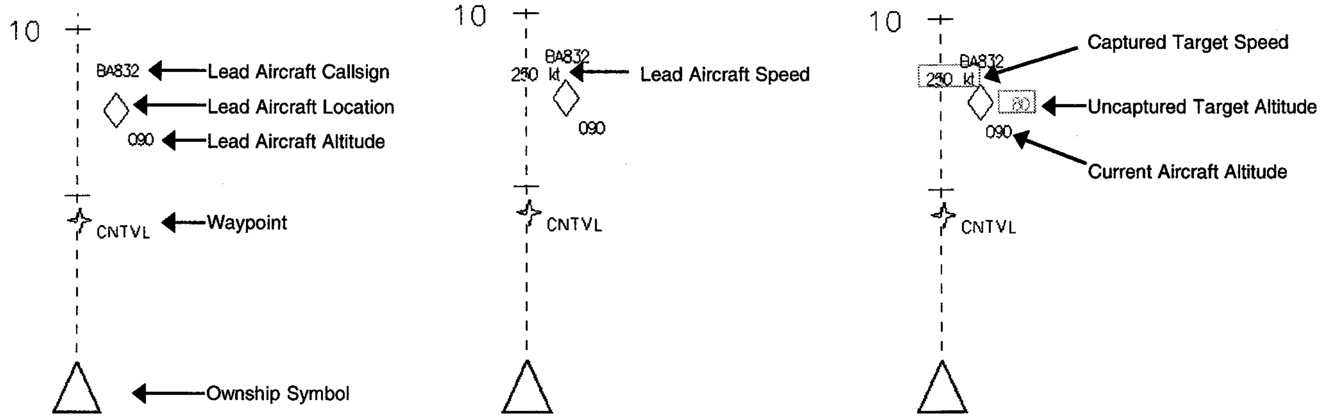
Subjects

The 12 subjects were all current pilots with a major airline. Total hours ranged from 6000 to 16,000 h. Five pilots were captains and seven were first officers. The pilots had flown Boeing 727, 737-800, 757, 767, MD80, MD88, and MD90 aircraft. All pilots but one had extensive experience with glass cockpits, and all were familiar with TCAS II and its associated CDTI. All pilots were uncompensated volunteers.

Independent Factors

CDTI

Three different CDTI were tested, differing only with the level of information provided about nearby traffic. All of the displays were based on the Boeing 757/767 electronic horizontal situation indicator (EHSI) with traffic information overlaid. In all cases, the displays provided information about the other aircraft that could potentially be provided by broadcast mechanisms such as automatic dependent surveillance–broadcast (ADS-B), with the traffic information updated once per second. Matching likely near-term implementations, the CDTI knew neither which aircraft was being followed nor the commanded separation.



a) Baseline display **b) Display with speed** **c) Display with speed and autopilot targets**

Fig. 1 Detail of the three CDTI.

1) The baseline display provided information about traffic based on the symbology currently employed by TCAS II,[19] as shown in Fig. 1a. An unfilled triangle represents the position of the subject-pilot's aircraft. Diamonds represent the horizontal positions of other aircraft, with altitude shown in text to their right. In addition to this TCAS II symbology, callsigns for the aircraft were shown textually above the position symbol.

2) The display with speed additionally indicated the current airspeed of nearby aircraft. Speed information is shown textually to the left of the aircraft symbol, as shown in Fig. 1b.

3) The display with speed and autopilot targets additionally indicated the autopilot target speeds and altitudes of nearby aircraft, as shown in Fig. 1c. Uncaptured autopilot target values are shown in magenta text inside a magenta box. On autopilot capture, the magenta box circles the actual speed or altitude, and the magenta text disappears.

Procedures

Three different procedures were tested, representing increased procedural information and environment predictability. These three procedures were presented to the pilot as three different types of STARs. Each was described by a chart using the same format as current STAR charts.

1) The baseline STAR chart presented the latitudes, longitudes, and altitudes of the waypoints comprising the STAR chart, as shown in Fig. 2a. Other information such as radio frequencies, airport locations, and navigation beacons were also shown, as typically found on current STAR charts.

2) The STAR with speed included the same information as the baseline STAR, with the addition of expected speeds at each waypoint, as shown in Fig. 2b. The expected speed is presented not as an air traffic control restriction, but rather as a rough estimate or recommendation for airspeed at a particular waypoint during typical traffic conditions.

3) The STAR with speed and merging path provides the same information as the STAR with speed, as well as a depiction of the other arrival stream into which the pilot will need to merge during the arrival. For example, in Fig. 2c, the two arrival segments merge at the ANNEJ intersection.

Scenarios

The underlying structure of all of the scenarios mimicked that of current STARs. However, the behavior of the other aircraft was modified to create two types of scenarios, nominal and deviant. In the nominal scenarios, the other aircraft all followed the published procedures closely, meeting expected speeds and maintaining the proper in-trail spacing. In the deviant scenario, all aircraft acted properly except for one instance: The aircraft the pilot was to merge behind suddenly slowed 50 kn below the expected speed as the pilot was starting to merge into the other traffic stream.

Test Matrix

The experiment consisted of two sequential parts that may be thought of as two separate experiments. There was no difference in the testing procedure for the two experiments, and the pilots were unaware they were partaking in two experiments.

The first experiment explored pilot ability to perform the given operations in nominal scenarios. This experiment examined two independent factors: all nine combinations of the three CDTI and three procedures. To prevent fatigue, a balanced-incomplete block experiment design was created in which each pilot only flew six of the nine combinations. No pilot flew the same procedure–CDTI combination or scenario twice, balancing against learning effects interfering with factor effects.

The second experiment explored pilot ability to perform the given operations in a deviant scenario. This experiment examined one independent factor: the three CDTI. Each pilot was given the STAR chart presenting the most procedural information. Each pilot flew only one deviant scenario to measure their performance when surprised. This scenario was each pilot's last (seventh) test run, eliminating subsequent runs in which they might modify their behavior.

Experiment Apparatus

Pilots flew arrival scenarios using the Georgia Institute of Technology Reconfigurable Flight Simulator software,[20] running on a Pentium II desktop computer. This setup simulated the pilot's aircraft and autopilot dynamics, simulated the dynamics of the other aircraft, and provided the cockpit displays, including the CDTI, on a 21-in. monitor in front of the pilot. Although a control column and throttle were placed by the pilot, the simulator in this study was flown through the autopilot by commanding autopilot modes and target airspeed, heading, vertical speed, and altitude.

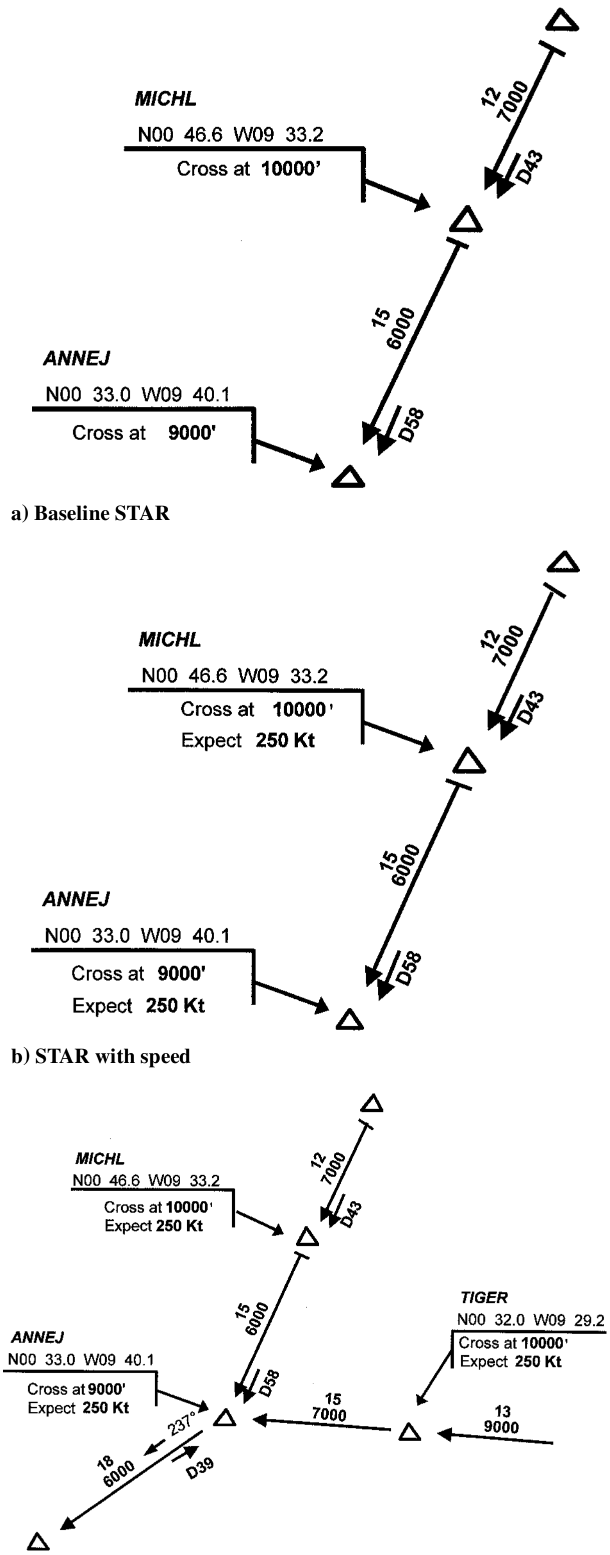
The display panel provided the pilot with a primary flight display (PFD), a combined EHSI–CDTI, a virtual mode control panel (MCP), and a field that, when selected, displayed the current STAR chart. The pilot was able to interact with these systems using a mouse; this was the means for the pilot to set autopilot commands, as well as for viewing the STAR chart and changing the display range of the traffic display.

Measurements

Several measures were taken throughout the experiment, including 1) spacing between the aircraft at every second, 2) all autopilot commands entered into the MCP, 3) all points at which pilots selected the display of the STAR chart, and 4) subjective responses at the conclusion of each test run and following the experiment.

Results

In total, 84 runs were flown: 72 in the primary experiment and 12 in the secondary experiment with the deviant scenario. The 12 deviant runs will be discussed separately from the 72 nominal runs.



a) Baseline STAR

b) STAR with speed

c) STAR with speed and merging path

Fig. 2 Detail of the three STAR chart formats.

Data Analysis Methods

Standard statistical techniques were used in analyzing the results.[21] Unless otherwise noted, the data were fit using regression techniques to a general linear model to perform an analysis of variance (ANOVA). Specifically, each measurement was assumed to be the sum of several terms: 1) the baseline value of the measurement over all conditions; 2) a "fixed effect" describing the change from overall as a result of the CDTI available to the pilot when the measurement was taken; 3) a fixed effect describing the change from overall as a result of the STAR available to the pilot when the measurement was taken; 4) a "fixed interaction effect" describing the change from overall as a result of the combination of CDTI and STAR available to the pilot when the measurement was taken (i.e., measuring the effect of specific combinations of CDTI and STAR beyond that predicted by their separate fixed increments); 5) an increment attributed to each pilot (termed a "random effect" because these increments were assumed to be normally distributed between pilots); and 6) a residual error remaining after the preceding terms were fit to the measurements, assumed to be normally distributed with zero mean.

Once these terms were computed, the mean squared error (MSE) was calculated as the sum of squares of the residual errors from the measurements, providing an assessment of the inherent variance in the measurements beyond that caused by the experiment factors, with an associated degree of freedom (DOF) indicating the number of measurements available for its calculation. Likewise, the mean square (MS) variances caused by each of the fixed effects (CDTI, STAR, and their interaction) and by the random effect (pilot), independent of residual error, were calculated with an associated DOF.

The ratio of the MS variance caused by a fixed effect to the MSE provides an assessment of the relative magnitude of an effect compared to the inherent variance in the measurements; this variance ratio (also called the Fisher statistic) is expressed as F (DOF of MS variance, DOF of MSE). The equivalent ratio of the MS variance caused by a random effect (in this study, the pilots) to the MSE assesses whether the variance between pilots is larger than that explained by the inherent variance between measurements and is also expressed using the same notation.

Each variance ratio can be compared to the Fisher or F distribution to find the probability p that this variance ratio does not represent, in the case of fixed effects, a statistically significant variance between the different conditions. (In this study, then, it is the probability that the CDTI, STAR, or their interaction did not cause significant differences in the measurements.) In the case of random effects, p indicates whether the variance of the random effects is larger than explained by MSE. (In this study, then, it is the probability that the measurements of different pilots were the same.) The following analysis uses $p < 0.05$ as the criterion to identify a statistically significant variation; pilots were always found to be significant sources of variation.

If a statistically significant variation was identified, the Tukey pairwise comparison procedure was used to identify specific factors that are different. For example, where the effect CDTI was found to be a source of variation, this procedure identified which specific pairs of CDTI had significantly different results. By the use of this procedure, ratios of the differences of each pair of factors to their standard deviation were calculated, thus generating a t statistic (as in a standard t test). However, in calculating the probability p that the difference is statistically significant, a more conservative value of the t statistic is applied; this criterion is set so that the total probability of incorrectly labeling a difference as statistically significant is bounded over the combination of all pairwise comparisons made, rather than just bounded for one pairwise comparison. In this case, the experimentwise error bound was set at $p = 0.05$, that is, the Tukey pairwise comparisons required 95% confidence to assess significance.

In some cases, ANOVA (and associated Tukey comparisons) were not appropriate because the condition that the residual errors be normally distributed was not found to hold. In these cases, the more conservative Wilcoxon rank-sum test was conducted because it does not place parametric assumptions on the results. This test ranks all of the data from greatest to least, and the ranks associated with the different conditions are compared to see if they are equivalently distributed. As in the other statistical tests, a 95% confidence level was used as the criterion of statistical significance (corresponding to a probability less than 0.05 of falsely identifying a difference).

In-Trail Spacing

A common segment of each arrival route was chosen in which to calculate in-trail spacing measures for each arrival. During this interval, the pilot was asked to achieve a spacing of 8 n miles in-trail,

Table 1 Pilot spacing at end of interval (percentage in 72 runs)

Pilots, %	Spacing achieved
47	Less than or equal to 0.25 n mile of commanded
22	Greater than 0.25 and less than or equal to 0.50 n mile of commanded
13	Greater than 0.50 and less than or equal to 0.75 n mile of commanded
18	Greater than 0.75 n mile of commanded

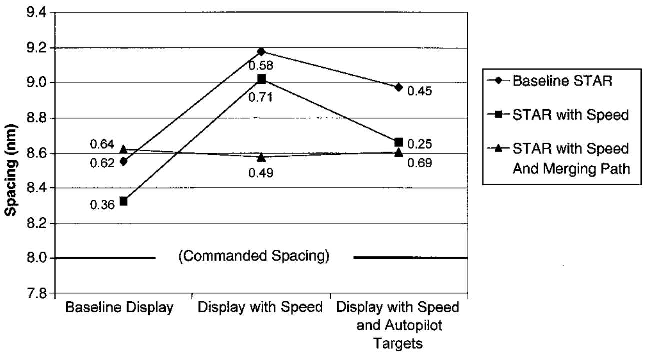


Fig. 3 Mean in-trail spacing, labeled with standard deviation (eight runs within each CDTI–procedure combination): ●, baseline STAR; ■, STAR with speed; and ▲, STAR with speed and merging path.

a reduction from the earlier spacing of 10 n miles in-trail. The mean spacings were grouped by CDTI–procedure combination, as shown in Fig. 3. These values are above 8 n mile because spacing at the start of the interval was 10 n mile. ANOVA revealed the presence of significant CDTI–procedure interactions, $F(4, 52) = 2.77$ and $p = 0.04$. A one-way ANOVA on the nine CDTI–procedure combinations found marginally significant variations $F(8, 52) = 1.93$ and $p = 0.17$. Tukey 95% pairwise comparisons revealed that the display with speed with the baseline STAR resulted in higher spacings than the baseline display with the STAR with speed.

On visual inspection of Fig. 3, little difference in spacing appears between CDTI when used with STAR with speed and merging path. To confirm this, a post hoc one-way ANOVA on the conditions with the STAR with speed and merging path was performed across CDTI. This test revealed that main effects due to CDTI do not exist, $F(2, 21) = 0.01$ and $p = 0.989$, in conditions with the STAR with speed and merging path.

Inspection of Fig. 3 also suggests that both the baseline STAR and STAR with speed appear to have similar effects. To analyze this, a post hoc two-way ANOVA was performed on the conditions with the baseline STAR and STAR with speed. The interaction effects found with the full data set were not significant in the data set containing only these two procedures, $F(2, 42) = 0.09$ and $p = 0.913$. Main effects due to procedures were not significant in this reduced data set, $F(1, 42) = 2.39$ and $p = 0.129$. However, significant CDTI effects were present, $F(2, 42) = 6.42$ and $p = 0.01$. Tukey 95% pairwise comparisons on the CDTI indicated that the baseline display resulted in significantly lower spacing values than the display with speed.

Another measure of pilot ability at spacing during the chosen arrival segment was obtained by taking the absolute value of the difference between the spacing the pilot had achieved at the end of the interval from the commanded value. Table 1 summarizes these results. Pilots achieved within 0.25 n mile of the commanded spacing in 34 runs (47%). In 50 of the 72 runs (69%) pilots were within 0.50 n mile.

Through analysis of the time it took the pilots to pass halfway from their earlier commanded spacing to their new commanded spacing for the same segment, behavior in obtaining the commanded spacing (specifically, the rate at which the pilots sought the new spacing) can be examined. Pilots failed to achieve half of the change in commanded spacing in 7% of the intervals; for computation purposes, the time at end of the interval was used in these cases. The mean time to reach half the change in commanded spacing is shown

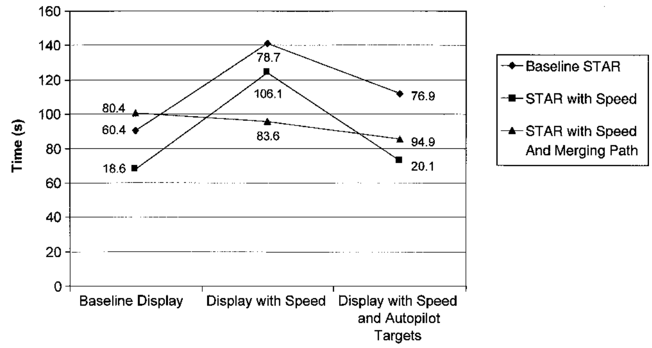


Fig. 4 Mean time to reach half of the change in commanded spacing, labeled with standard deviation (eight runs within each CDTI–procedure combination): ●, baseline STAR; ■, STAR with speed; and ▲, STAR with speed and merging path.

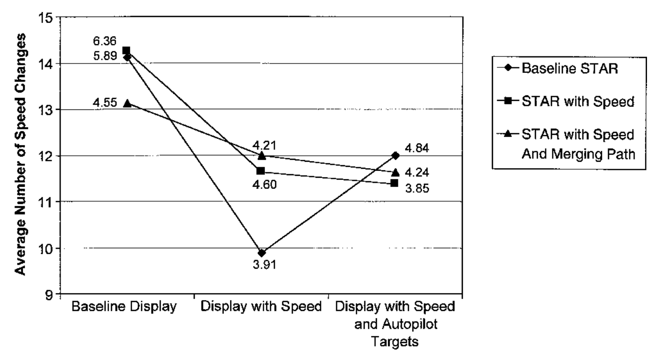


Fig. 5 Mean number of speed changes during each arrival, labeled with standard deviation (eight runs within each CDTI–procedure combination): ●, baseline STAR; ■, STAR with speed; and ▲, STAR with speed and merging path.

in Fig. 4. Because the data did not follow a normal distribution, a Wilcoxon 95% rank sum test was used for analysis. Conditions with the display with speed and baseline STAR had significant longer times to achieve half of the change in commanded spacing than pilots provided with either the baseline display and STAR with speed or the display with speed and autopilot targets and STAR with speed.

Comparison of Figs. 3 and 4 reveals some similar trends because their two measures may be capturing different elements of the same behavior. Pilots requiring more time to attain half of the change in commanded spacing often had higher mean spacing values due to the duration with higher spacing integrated into the mean spacing calculation.

In summary, these measures both found significant interactions between CDTI and procedures when examined in the aggregate. These interactions may arise from two behaviors: a lack of CDTI effect when the STAR with speed and merging path was available and a significant CDTI effect with the other two STARs.

Spacing is not the only measure of performance. The smoothness of the flight, as indicated by the number of speed changes made by the pilots during each run, is also important because higher numbers are generally indicative of poorer fuel efficiency and higher pilot workload (although fuel efficiency and pilot workload were not directly measured in this experiment). The mean number of speed changes made by the pilots during the entire arrival is shown in Fig. 5. ANOVA revealed the presence of marginally significant CDTI effects, $F(2, 52) = 2.83$ and $p = 0.068$. Neither CDTI–procedure interaction effects, $F(4, 52) = 1.11$ and $p = 0.360$, nor procedure effects, $F(4, 52) = 0.10$ and $p = 0.909$, were significant. Analysis of Tukey 95% pairwise comparisons revealed that when provided with the baseline display, pilots made more speed changes than when either of the other two displays were provided.

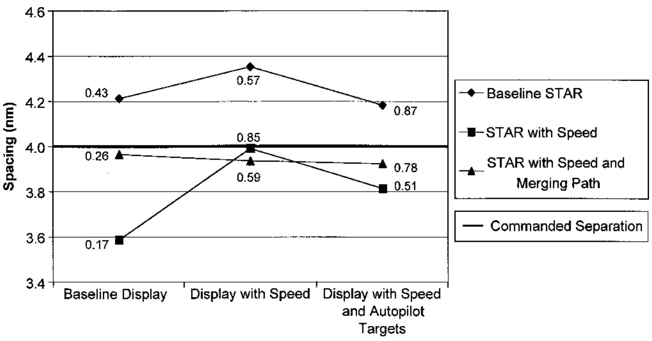


Fig. 6 Mean merging spacing, labeled with standard deviation (eight runs within each CDTI–procedure combination): ●, baseline STAR; ■, STAR with speed; and ▲, STAR with speed and merging path.

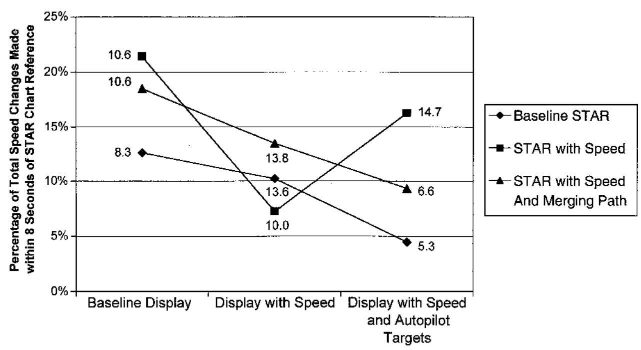


Fig. 7 Mean percentage of airspeed changes made within 8 s following a STAR reference, labeled with standard deviation (eight runs within each CDTI–procedure combination): ●, baseline STAR; ■, STAR with speed; and ▲, STAR with speed and merging path.

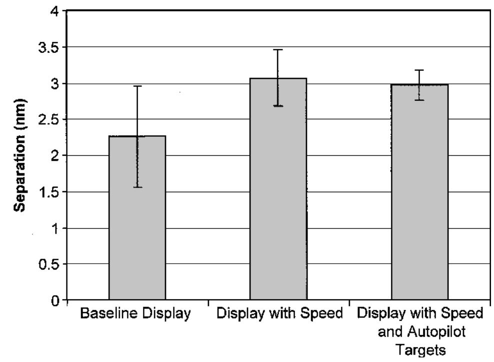


Fig. 8 Deviant scenario mean separation values from merge point to end of arrival (four runs within each CDTI condition; error bars represent standard deviation).

Merging

The merging operation required each pilot to cross behind another aircraft at the merge point and then follow behind that aircraft while maintaining 4 n miles in-trail spacing. As a measure of pilot merging ability, the mean merge spacings were obtained from when the aircraft ahead of the pilot crossed the merge point until the end of the pilot's run, as shown in Fig. 6. The mean separations fall between 3.5 and 4.4 n mile. ANOVA found neither significant CDTI effects, nor procedure effects, nor interactions between CDTI and procedures.

Procedure Usage

It was hypothesized that pilots may use the STAR chart for speed information. If this were true, speed changes would commonly be made shortly after referencing the STAR chart. In an attempt to assess pilot use of procedures, the number of STAR chart references made by each pilot within the 8 s preceding an airspeed change was counted. These trends varied widely between pilots, with some frequently referencing the STAR chart before a speed change, and others never doing so. The mean values across pilots are shown in Fig. 7. ANOVA found that CDTI–procedure interactions were not significant, $F(4, 52) = 0.79$ and $p = 0.535$. However, both CDTI, $F(2, 52) = 3.06$ and $p = 0.06$, and procedures, $F(2, 52) = 2.83$ and $p = 0.07$, were marginal sources of variation. Tukey 95% pairwise comparisons of displays revealed that a higher percentage of speed changes in the 8 s following STAR chart access when the baseline display was available than when the display with speed was available. Tukey 95% pairwise comparisons of procedures showed that the baseline STAR resulted in a lower percentage of speed changes in the 8 s following its access than the STAR with speed and merging path.

The total number STAR chart references over each test run was similarly analyzed. Although ANOVA showed that both CDTI–procedure interaction effects, $F(4, 52) = 1.53$ and $p = 0.21$, and CDTI effects, $F(2, 52) = 0.49$ and $p = 0.62$, were not significant, the procedure was a significant source of variation, $F(2, 52) = 3.28$ and $p = 0.05$. As found with references to the STAR chart immediately before a speed change, Tukey 95% pairwise comparisons on procedure level indicated that the baseline STAR had fewer references than did the STAR with speed and merging path.

In summary, pilots were found to refer more to the STAR charts that contained more proceduralized information, both in general and in the 8 s before making a speed change. Although large variability existed between pilots, these results suggest that many treated the STAR chart as an information source.

Effect of the Deviant Scenario

In the deviant scenario, the pilot was confronted with a situation where the published procedure was not followed by the aircraft the pilot was to merge behind, that is, the lead aircraft slowed to a speed 50 kn slower than the speed on the STAR chart. Figure 8 presents the mean separation values as a function of CDTI. In current air traffic control operations, separation below 3 n mile horizontally and 1000 ft vertically is considered a separation violation. Each of the 12 pilots violated this minimum separation requirement at some point during the deviant scenario. The mean separation values were below this required separation value except in conditions with display with speed. Two pilots failed to regain at least 3 n mile of horizontal separation before the run ended. ANOVA found marginally significant CDTI effects, $F(2, 9) = 3.05$ and $p = 0.10$; however, Tukey 95% pairwise comparisons found no significant differences between display conditions. The overall low separation values suggest that pilots may have difficulty noticing and/or reacting to other pilots' deviations from procedures.

Pilot Opinions

When asked at the end of the experiment about the feasibility of performing in-trail spacing, 11 of the 12 pilots felt the operation could be performed, but with qualifications such as increased training and equipment, as well as display and procedural modifications. Of the 12 pilots, 11 cited current airspeed as a helpful component to the traffic display when performing in-trail spacing. Target airspeed was viewed as helpful, but not as necessary as current airspeed. Pilots also cited the ability of range marks to help judge spacing distances.

When asked about pilot-performed merging, 10 of the 12 pilots believed it was feasible. However, all but one of the pilots qualified their response. Such qualifications include, but are not limited to, ATC intervention in the event of "trouble"; need for proceduralized, adhered-to speeds and clarification of spacings at merge; a time to cross fix (intersection); and a published escape maneuver out of the merging area. Of the 12 pilots, 9 cited current airspeed as an aid during in the merging operation. The relative position of other traffic was also cited by seven of the pilots as an aid.

The main complaint by pilots about the presentation of information across all three CDTI was the high degree of clutter. This was especially true for the display with speed and autopilot targets. Many pilots offered suggestions that would enable the pilot to declutter the display. However, using redundant pairwise-comparisons analyzed by the analytic hierarchy process,[22] pilots rated the display with speed and autopilot targets (the most informative and cluttered) over the display with speed by a ratio of nearly 2:1, considered a slight preference. Pilots rated the display with speed and autopilot targets over the baseline display by a ratio of 10:1, considered an extremely strong preference. Pilots rated the display with speed over the baseline display by a ratio of 5:1, considered a strong preference.

Pilots also had strong opinions about the utility of the STAR charts. When asked if the STAR provided support for the in-trail spacing operation, all 12 pilots concluded that the STAR was helpful due to the inclusion of expected speeds at each waypoint. All 12 of the pilots cited some aspect of the STAR as being helpful in supporting the merging operation. Of the 12 pilots, 10 cited the merge depiction as being helpful. The two pilots who did not cite the merge depiction felt that the expected airspeed was helpful when merging.

By the use of redundant pairwise comparisons analyzed by the analytic hierarchy process,[22] pilots were found to prefer the STAR with speed and merging path to the STAR with speed by a slim margin for in-trail spacing and a relatively wide margin for merging. A strong preference for the STAR with speed and merging path was indicated over the baseline STAR. Pilots possessed a moderately strong preference for the STAR with speed over the baseline STAR. The STAR with speed was slightly preferred over the baseline STAR for the merging operation.

Pilots cited altitude, airspeed, upper speed bands, and some sort of allocated protective maneuvering space as potential components that could be mandated by the STAR, especially for support of in-trail spacing and merging. One pilot noted that, if the STAR mandated airspeed within a certain range, for example, ± 10 kn, and if controllers held pilots to those published speeds, displaying other aircraft speeds would be unnecessary.

Conclusions

The results of this study suggest that pilot performed in-trail spacing is a potentially viable operation worthy of further investigation; 11 of 12 pilots felt that it was feasible with the CDTI and procedures tested. The results on pilot-performed merging were positive, albeit with qualifications. Pilots suggested a need for both technology enhancements, display of other aircraft airspeed, automated speed-up/slow-down cues near the merge, and procedural changes, proceduralized speeds, published escape maneuvers in case of difficulties in achieving the correct spacing, and a controller-specified time to cross the merge point. In all cases, pilots also voiced strong opinions about a continued, active role for the controller. Their comments highlighted a desire for the controller to continue to have several responsibilities, including oversight of safety, centralized organization of the traffic flow, and monitoring for (and resolution of) nonprocedural actions taken by any pilot.

The results of this study provide only a preliminary assessment: The fidelity of the simulation confounded the spacing and merging performance of the pilots with the limitations of its dynamic models of the aircraft and autopilot; the single-crew, part-task nature of the runs prevented in-depth analysis of workload; only the arrival phase of flight was examined; and the low number of subjects limited the power of the statistical analysis. Likewise, the only stochastic and reactive element in this study stemmed from the pilots themselves. However, these tentative results suggest more extensive research into these types of operations may be fruitful. The results provide the first step in showing that the pilots are capable of greater involvement in their own guidance within the NAS when all of the other aircraft are following open-loop, prespecified speed profiles. However, these results cannot necessarily be extended to a stream of aircraft, each maneuvering to maintain relative positions, without further pilot-in-the-loop studies with multiple pilots in series investigating the overall stability of the traffic flow.

Statistical interactions were found between the effects of CDTI and the effects of procedures in many measures in this study, including pilot performance at in-trail spacing and the accelerations used to achieve these spacings. These statistical interactions have the practical implication that CDTI and airspace procedures do not function independently of each other. Like CDTI, procedures may be a source of guidance information to the pilot. In this study, pilots were found to refer to STAR charts more frequently when the charts had more information and when the CDTI provided less. At an extreme, as one pilot noted, if the procedure requires a specific speed range of all aircraft, then a presentation of aircraft speed on the CDTI is not required. This highlights the careful consideration that should be given to procedural information in testing CDTI. Any CDTI is likely to be tested and demonstrated in the current ATM environment, with its commensurate procedures. Such testing alone does not necessarily guarantee that the CDTI will be an adequate information source in future ATM environments where different procedures may provide less, or different, information.

The importance of procedural information found in this experiment highlights the challenge to balance the pilots' need for procedures with the need for the NAS to be flexible and responsive to changing conditions. Future ATM guidance procedures, it may be reasonably hypothesized, may not need to be as permanent and inflexible as they are currently. Rather than needing to be published in paper (with a commensurate lack of flexibility), their utility in providing foreknowledge and expectations may possibly be provided by electronic presentations of that day's (or that hour's) traffic flow plan, uplinked to a cockpit display.

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References

[1]Ballin, M. G., and Erzberger, H., "Potential Benefits of Terminal Airspace Traffic Automation for Arrivals," *Journal of Guidance, Control, and Dynamics*, Vol. 21, No. 6, 1998, pp. 909–915.

[2]Erzberger, H., and Nedell, W., "Design of Automated System for Management of Arrival Traffic," NASA TM-102201, June 1989.

[3]Leroux, M., and Gaillard, I., "Evaluation of Decision Aids for En-Route Air Traffic Controllers," *Proceedings of the Eighth International Symposium on Aviation Psychology*, Ohio State Univ., Columbus, OH, 1995.

[4]Denery, D. G., Erzberger, H., Davis, T. J., Green, S. N., and McNally, B. D., "Challenges of Air Traffic Management Research: Analysis, Simulation, and Field Test," AIAA Paper 97-3832, Aug. 1997.

[5]Green, S. M., and Vivona, R. A., "En Route Descent Advisor Concept for Arrival Metering," AIAA Paper 2001-4114, Aug. 2001.

[6]Rognin, L., Grimaud, I., Hoffman, E., and Zeghal, K., "User-Centered Design of Cockpit Interfaces Involving Pilots in Sequencing Operations," AIAA Paper 2001-4177, Aug. 2001.

[7]Hoffman, E., Grimaud, I., Rognin, L., and Zeghal, K., "Delegation of Crossing Operations to the Flight Crew: First Quantitative Results," AIAA Paper 2001-4178, Aug. 2001.

[8]Mellone, V. J., and Frank, S. M., "Behavioral Impact of TCAS II on the National Air Traffic Control System," *Proceedings of the Seventh International Symposium on Aviation Psychology*, Ohio State Univ., Columbus, OH, 1993.

[9]Williams, D. H., and Wells, D. C., "Jet Transport Operations Using Cockpit Display of Traffic Information During Instrument Meteorological Conditions," NASA TP-2567, May 1986.

[10]Sorensen, J. A., and Goka, T., "Analysis of In-Trail Following Dynamics of CDTI-Equipped Aircraft," *Journal of Guidance, Control, and Dynamics*, Vol. 6, No. 3, 1983, pp. 162–169.

[11]Williams, D. H., "Time-Based Self-Spacing Techniques Using Cockpit Display of Traffic Information During Approach to Landing in a Terminal Area Vectoring Environment," NASA TM-84601, April 1983.

[12]Zeitlin, A., Love, D., and Cieplak, J., "Enhancements to the Next Generation of Collision Avoidance System; Opportunities for Greater Safety and Efficiency," MITRE Corp., McLean, VA, 1995.

[13]Merwin, D. H., and Wickens, C. D., "Evaluation of Perspective and Coplanar Cockpit Displays of Traffic Information to Support Hazard Awareness in Free Flight," Aviation Research Lab. Inst. of Aviation, ARL-96-5/NASA-96-1, Univ. of Illinois at Urbana-Champaign, Urbana, IL, 1996.

[14]Barhydt, R., and Hansman R. J., "Experimental Studies of Intent Information on Cockpit Traffic Displays," *International Symposium for Aviation Psychology*, Ohio State Univ., Columbus, OH, 1997, pp. 261–267.

[15]Degani, A., and Wiener, E. L., "Procedures in Complex Systems: The Airline Cockpit," *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 27, No. 3, 1997, pp. 302–311.

[16]"Report of the RTCA Board of Directors' Select Committee on Free Flight," RTCA, Inc., Washington, DC, 1994.

[17]Wickens, C. D., *Engineering Psychology and Human Performance*, HarperCollins, New York, 1992, pp. 445–474.

[18]Hollnagel, E., *Human Reliability Analysis: Context and Control*, Academic Press, London, 1993, pp. 175–183.

[19]"Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System (TCAS) Airborne Equipment," RTCA, Inc., RTCA/DO–185, Washington, DC, 1983.

[20]Pritchett, A. R., and Ippolito, C. A., "Software Architecture for a Reconfigurable Flight Simulator," AIAA Paper 2000-4501, Aug. 2000.

[21]Hogg, R. V., and Ledolter, J., *Applied Statistics for Engineers and Physical Scientists*, 2nd ed., Macmillan, New York, 1992.

[22]Yang, L., and Hansman, R. J., "Application of the Analytic Hierarchy Process for Making Subjective Comparisons Between Multiple Automation/Display Options," *Analysis, Design and Evaluation of Man–Machine Systems*, edited by T. B. Sheridan, Vol. 2, Pergamon, New York, 1995, pp. 487–491.