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Experimental Studies of Intent Information on Cockpit Traffic Displays

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An initial experiment was conducted to examine the use of intruder aircraft intent information on prototype cockpit traffic displays. The current Traffic Alert and Collision Avoidance System (TCAS) plan-view display was used as a baseline. Displays corresponding to three additional intent levels (rate, target state, and trajectory) were tested, with higher levels representing a more complete knowledge of an intruder aircraft's intended trajectory. Intent-enhanced displays added an automation-based conflict probe and a profile-view display. The experiment, run on a Massachusetts Institute of Technology part-task flight simulator, required pilots to maintain a minimum separation from intruder aircraft in a variety of traffic situations. Pilots maneuvered earlier and had fewer separation violations with the three enhanced displays. A follow-up experiment, using the same apparatus and procedure, was performed to determine the display features most responsible for the differences observed in the first experiment. Providing intent information directly on the display or incorporating it into a conflict probe both led to fewer separation violations and earlier maneuvers when compared to the Basic TCAS display.

Introduction

WITH the evolution toward a more unstructured air-traffic management system underway, pilots may eventually incur more responsibility for maintaining separation from other traffic.[1] To allow pilots to make informed decisions about potential conflicts, researchers are working on enhancements to the current Cockpit Display of Traffic Information (CDTI), a component of the Traffic Alert and Collision Avoidance System (TCAS). Pilots will likely require traffic displays that provide more information about an intruder aircraft's intended trajectory. The Federal Aviation Administration (FAA) has stated that this information, hereafter referred to as *intent information*, will play a crucial role in the development of a new air-traffic management system.[1] Intent information exists at many different levels, ranging from an aircraft's current state to a series of expected future states. In order of the increasing level of intent, this information may include an intruder's current position, velocity, commanded heading and altitude (if maneuvering), and future waypoints. Higher levels of intent represent a more complete knowledge of another aircraft's intended trajectory.

Several prior studies have investigated the effects of current state level intent information.[2–5] When compared to displays that only provided an intruder aircraft's current position and altitude (such as TCAS), the addition of a rate-enhanced predictor significantly improved a pilot's ability to determine the future position of intruder aircraft.[2,3] Consequently, predictors also reduced the instances of lost traffic separation.[4] Although the benefits of rate-enhanced displays are well known, little work has been done to examine the benefit of higher levels of intent, such as commanded state and multiple future state information.

Recent advances to datalink systems[6] have enabled researchers to consider the application of higher levels of intent in the development of a next generation CDTI. A study by Zeitlin et al. predicts that commanded state information will improve the accuracy of TCAS conflict predictions.[7] Duong and Hoffman have run computer simulations on prototype displays, showing conflict regions based on future ownship waypoints.[8] In developing a new CDTI, determining whether pilots will be able to use this complex intent information to better resolve traffic conflicts will be important. Without a noticeable improvement in pilot performance, justifying the added system complexity and expense associated with providing intent information may be difficult.

In addition to datalink capability, the amount of intent information available for display on a CDTI depends in large part on an intruder aircraft's current operating mode and equipment. The three primary operating modes, referred to here as manual, state, and trajectory, are diagrammed in Fig. 1. With each additional outer loop the pilot communicates more intentions about future states to his own aircraft, thus enabling it to be exchanged with other aircraft, assuming a capable datalink system. Intent information outside the loop of an aircraft's current operating mode represents unknown states and therefore cannot be transmitted to other aircraft. Figure 1 also shows the aircraft equipment required to operate in each of the three control modes. Older or less complex aircraft may not have the necessary architecture to broadcast higher levels of intent information.

Manual mode is the innermost and simplest control loop. When flying manually, the pilot bypasses the autopilot and commands the aircraft directly with the flight controls. The available intent information is limited to current state variables such as heading, altitude, airspeed, and vertical speed.

The middle control loop is referred to as the *state mode*. Instead of controlling the aircraft directly, the pilot issues a target state to the autopilot. Commanded states, such as heading or altitude, are entered into a mode control panel. The autopilot makes the necessary control inputs to achieve the desired state. In this mode the aircraft's current and commanded state variables become known parameters.

The outermost loop is the trajectory mode. At this level the pilot currently interacts with a keypad-based control display unit to command multiple future states. The pilot may enter an entire trajectory complete with waypoints, crossing altitudes, and speed restrictions. Future systems could allow the pilot to specify a waypoint arrival time. The flight management system (FMS) determines where climbs and descents should begin and where speed changes should occur in order to achieve the desired trajectory. Aircraft equipment limitations are most prevalent in this mode. Many older aircraft, such as the Boeing 727 and Douglas DC-9, do not have FMS and are therefore unable to transmit trajectory level information.

New display features may be necessary to allow pilots to interpret more complex intruder aircraft trajectories. Providing a clear depiction of vertical information is one of the major challenges of CDTI design.[9] An experiment by Ellis et al. showed that pilots were more likely to perform a vertical avoidance maneuver and achieve the required separation from intruder aircraft when using a perspective display in place of a plan-view display.[10] Wickens and Mervin

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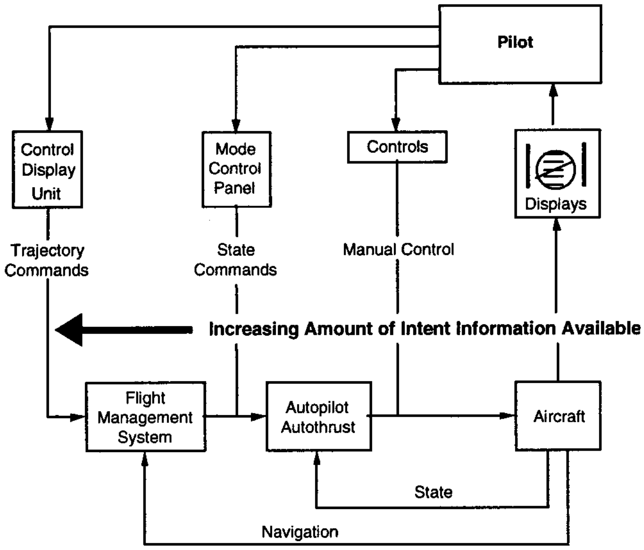

Fig. 1 Aircraft mode diagram.

conducted an experiment to determine if the performance of a plan-view display could be improved by presenting the vertical information on a companion profile-view display instead of a traditional data tag.[11] They determined that pilots had fewer traffic conflicts with the coplanar (plan and profile view) display than with a perspective display. In a related study Vakil found that the addition of a profile-view display to a standard plan-view map display improved pilots' ability to predict autoflight mode transitions and interpret vertical path information.[12] A coplanar format may also be more compatible with existing equipment because horizontal information can be shown on an existing plan-view display.

Another prominent display enhancement currently under consideration is the conflict probe, an automation-assisted tool used to predict potential traffic conflicts. A conflict probe determines likely areas of lost separation by extrapolating the position of ownship and intruder aircraft. By helping pilots become aware of potential conflicts, it is believed that crews can conduct smaller and more efficient avoidance maneuvers.[13,14] The complexity of current conflict probe models ranges from deterministic extrapolations based on current velocity[13] to estimates of conflict probability that consider random position errors[13,14] and intentional changes in heading and altitude.[14] When the conflict probe detects a threat, the pilot is usually alerted by a display feature that shows the intruder aircraft and conflict region. Some prototype systems allow the pilot to probe a series of avoidance maneuvers to determine the most desirable outcome.[5] Others provide an optimal avoidance solution in certain simple encounters.[15]

Three levels of intent, corresponding to the manual, state, and trajectory operating modes, were chosen for study in an initial experiment. The rate level represented the manual mode and incorporated information about an aircraft's current state. The commanded state level added first target state commands to the current state variables available at the rate level. The FMS-path level, which corresponded to the trajectory mode, included information about the FMS-programmed lateral (LNAV) and vertical (VNAV) navigation paths. Additionally, the current TCAS was used as a baseline and represented the lowest level of intent information.

Experiment 1: Levels of Intent Information

Objective

An experiment was conducted to identify the levels and specific elements of intent information most effective in enabling pilots to recognize and resolve traffic conflicts. To evaluate the ability of pilots to use the information, prototype displays corresponding to the TCAS, rate, commanded state, and FMS-path levels of intent were developed. Pilots flew several traffic scenarios with each of the four displays.

Prototype Displays

Each traffic display was superimposed onto a map display based on the Boeing format and color conventions.[16] All displays included the aircraft identification (ID) and used current TCAS symbology to represent the position and relative altitude of other aircraft. The appropriate amount of intent information was added to the three enhanced displays (rate, commanded state, and FMS-path). TCAS II logic, including traffic alerts and resolution advisories, was available on all displays. Sample displays for the same traffic situation are provided in Figs. 2a–2d. Display figures have been video inverted for clarity.

The enhanced displays incorporated three major additions to the TCAS display: intent information, a conflict probe, and a profile-view display. Display format was based on existing conventions and the results of numerous studies on CDTI design.[5,9–15] The profile-view display was modeled after Vakil's prototype Electronic Vertical Situation Display.[12] It showed a projection of the traffic situation onto the ownship velocity vector. Distance is plotted ahead of the ownship and at the absolute altitude. A simple, deterministic conflict probe determined potential conflicts using trajectory information consistent with the level of intent being evaluated. A conflict band, drawn along the ownship flight path, and various color changes alerted pilots to the presence of a detected threat.

The lowest level of intent is represented by the current TCAS display (with aircraft ID added), shown in Fig. 2a. The intruder aircraft is drawn as an open white diamond. The up arrow, drawn between the traffic symbol and the aircraft ID, indicates a climb rate of at least 500 ft/min. In Fig. 2a the intruder's altitude is 700 ft lower than the ownship. The relative altitude is depicted below the traffic symbol. If TCAS anticipates a conflict based on the range and range rate between the ownship and intruder, the traffic symbol changes color and/or shape to indicate the level of threat. Proximate traffic is drawn as a filled white diamond. If a traffic advisory is issued, the intruder symbol is a filled yellow circle. Threat aircraft requiring a resolution advisory are drawn as a filled red square.

On the rate display, shown in Fig. 2b, the intruder's ground-referenced heading is represented by a short arrow drawn from the center of the traffic symbol. The conflict probe linearly extrapolated the ownship and intruder velocities to determine where defined separation criteria between the two aircraft would be violated if both aircraft maintain their present track. The conflict band shows the region along the ownship flight path where the distance from the

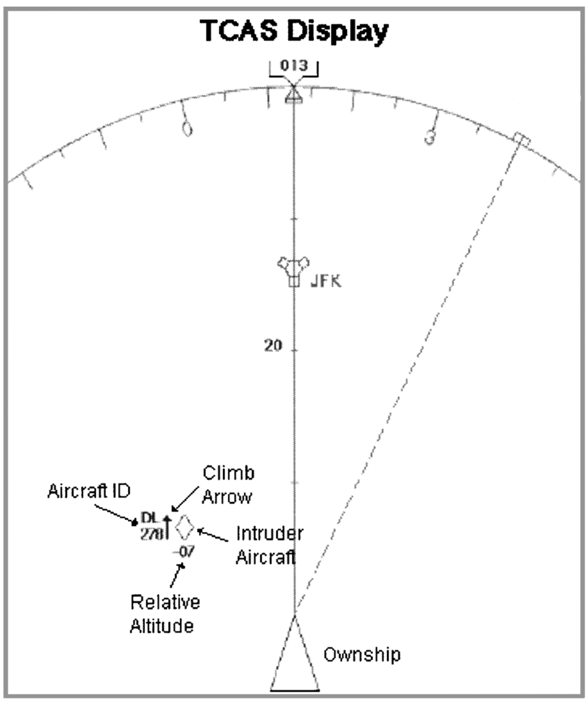

Fig. 2a TCAS display (video inverted for clarity, actual display had black background).

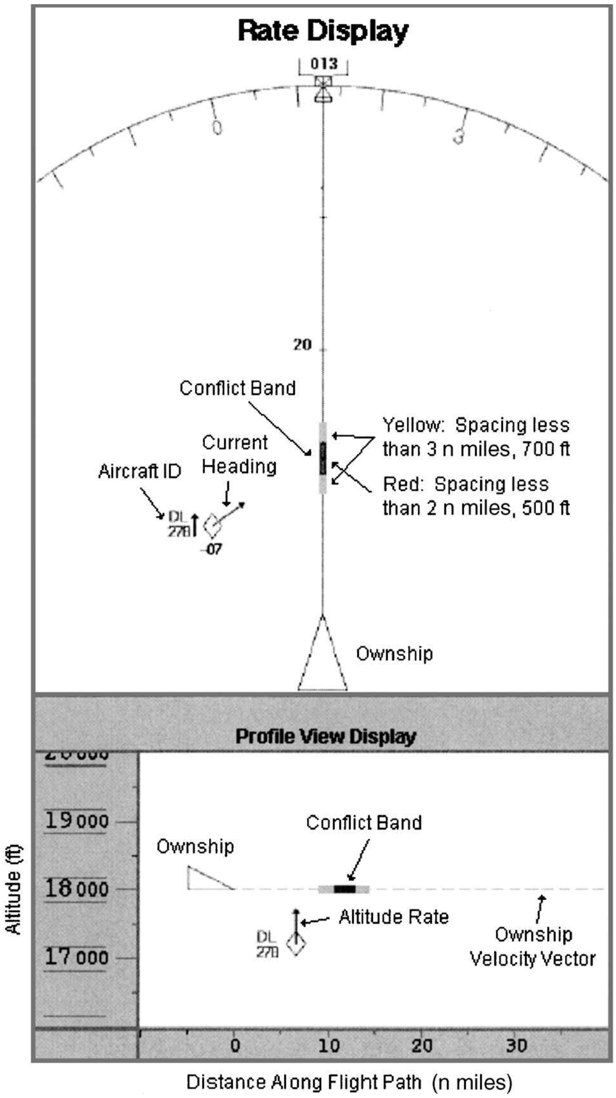

Fig. 2b Rate display (video inverted for clarity, actual display had black background).

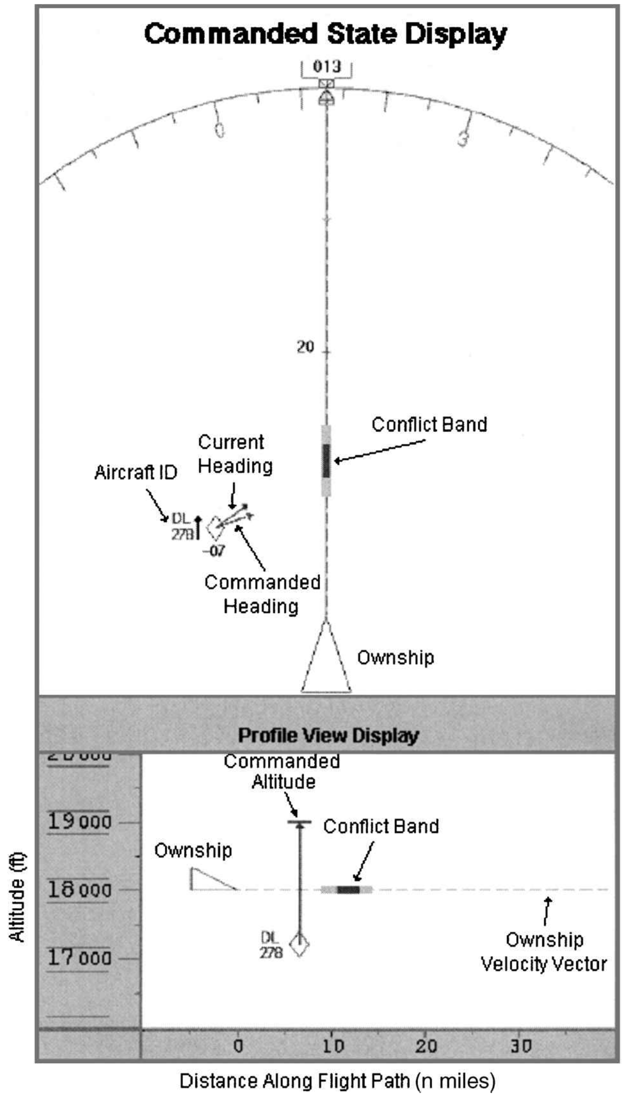

Fig. 2c Commanded-state display (video inverted for clarity, actual display had black background).

intruder is projected to be less than 2 n miles laterally and 500 ft vertically (red) or 3 n miles laterally and 700 ft vertically (yellow). The aircraft ID, drawn next to the traffic symbol, and the heading arrow were either white, yellow, or red, consistent with the level of threat. In addition, an up or down arrow was drawn from the traffic symbol on the profile view display if an intruder's climb or descent rate exceeded 500 ft/m.

The commanded-state display (Fig. 2c) shows the commanded heading and altitude for maneuvering aircraft. The commanded heading is shown as a magenta arrow drawn from the center of the traffic symbol, and the commanded altitude is drawn as a short magenta line on the profile-view display. Magenta was chosen to be consistent with Boeing's convention for showing fly-to information.[16] The conflict probe did not consider commanded-state information and was identical to that used for the rate display.

The LNAV and VNAV paths, which include future waypoints and crossing altitudes, are drawn in magenta on the FMS-path display, shown in Fig. 2d. Waypoint crossing altitudes are with respect to the ownship's predicted altitude (based on current vertical speed) when the intruder arrives at the waypoint. A conflict band was drawn on the ownship's path if a potential conflict was predicted, based on an intruder's current velocity or FMS-path information. Because of uncertainties in an airplane's VNAV path, such as wind, air temperature, and aircraft architecture, several simplifying assumptions were incorporated into the FMS-path based conflict probe. The assumption was made that the intruder would cross each waypoint exactly at the crossing altitude and would fly at constant airspeed and vertical speed between waypoints. These assumptions matched the simulated intruders' preprogrammed flight paths.

Apparatus

The experiment was conducted on a Massachusetts Institute of Technology (MIT) part-task flight simulator. A Silicon Graphics workstation controlled the dynamics for the ownship and intruder aircraft. A control side stick was provided for manual control, and autopilot control was accomplished through a mode control panel. Aircraft displays were shown on the computer screen. Pilots were provided with a B-747-400 style primary flight display and the map/traffic display. The traffic display range could be adjusted with keyboard buttons. In an effort to reduce display clutter, intent information was only shown for aircraft projected to cause a conflict. Pilots could choose to show intent information for nonconflict aircraft by clicking on the aircraft symbol with the computer mouse. During the experiment, the subject pilot could always access the appropriate amount of intent information from intruder aircraft. To satisfy this requirement, assumptions were made that a capable datalink system was available and that intruder aircraft were sufficiently equipped and always operated in the trajectory mode.

Experimental Design

The experiment incorporated a 4 Display by 5 Scenario within-subjects factorial design with counterbalanced display order. An initial briefing explained the simulator apparatus and scenario objectives. Prior to running scenarios for a new display, pilots were asked to fly practice traffic scenarios until familiar with the display symbology and the handling qualities of the simulator. After completing all scenarios subject pilots filled out a questionnaire asking them to rate the displays and the various elements of intent information.

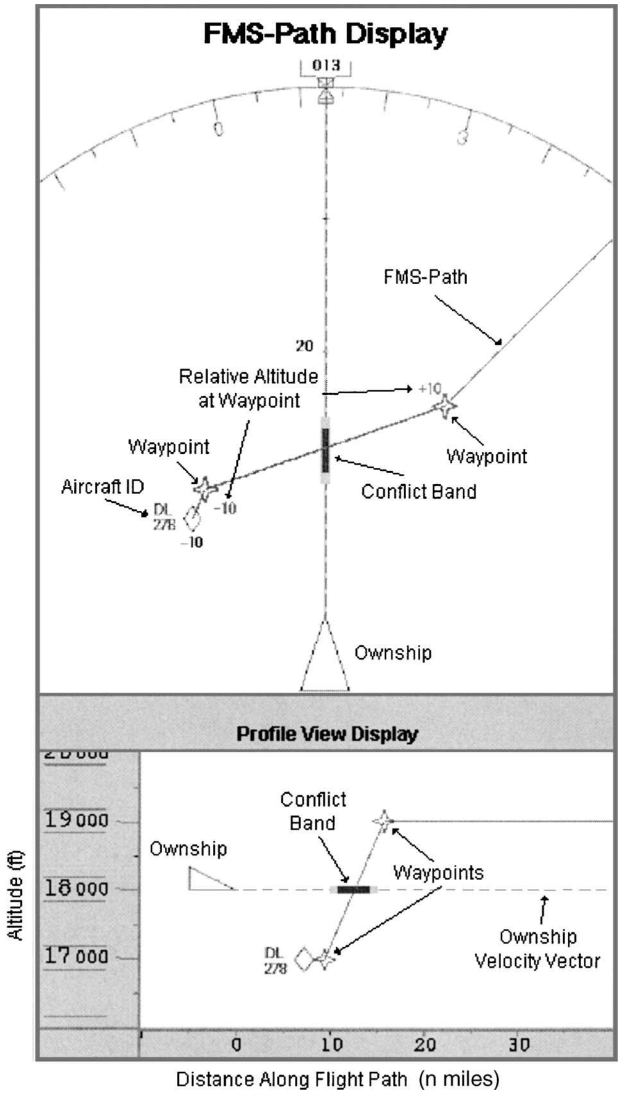

Fig. 2d FMS-path display (video inverted for clarity, actual display had black background).

Subjects

Eight current commercial airline pilots from major U.S. carriers served as volunteer test subjects in the experiment. They all had experience on glass cockpit and TCAS-equipped aircraft. Their experience ranged from 5,000 to 24,000 h with a mean of 10,875 h and their age ranged from 39 to 53 with a mean of 46.

Scenarios

Five scenarios were designed to represent a variety of common traffic situations. Scenarios consisted of an intruder overtake, intruder trajectory change, ownship overtake, long-range conflict, and a dual conflict. Six background aircraft flew trajectories in reasonable proximity to the ownship to deflect some of the pilot's attention away from the conflict-causing aircraft. The dual conflict scenario included two designed conflicts, whereas all others had only one. All intruders flew preprogrammed flight paths, independent of the subject pilot's actions. The scenarios were designed to be difficult in an effort to highlight the differences in display effectiveness. To reduce the likelihood of pilots recognizing a previously run scenario, intruder aircraft were mirror imaged laterally and vertically to produce four versions of each scenario. Scenario versions were evenly distributed among the four displays.

Task

The primary objective of each scenario was to maintain a minimum 2 n miles lateral or 500 ft vertical separation from all other traffic. Unless maneuvering to avoid a conflict, pilots were to fly directly to a destination waypoint at the initial altitude of 18,000 ft. They were instructed to turn toward the destination and return to 18,000 ft as soon as possible after resolving a conflict. The flight environment consisted of a completely unstructured air-traffic management system. No air-traffic control was available, and pilots were not asked to conform to any existing procedures when resolving conflicts. Pilots had full responsibility for maintaining their own traffic separation and were free to maneuver in any manner at any time.

Results

Data Analysis

Analysis of performance data focused on the ability of the intent displays to reduce the number of separation violations (pilot failed to remain at least 2 n miles or 500 ft from other traffic) and on the time the pilot initiated an avoidance maneuver. McNemar tests for correlated proportions, with a one-tailed t test, were performed to compare the separation violation percentages between the TCAS and the three intent displays.[17] To account for the higher level of uncertainty associated with multiple t tests, a Bonferroni correction for three comparisons was applied to the indicated p values (significance levels).[18] Maneuver time data were analyzed with paired two-tailed t tests, performed on all combinations of the four displays (TCAS, rate, commanded state, and FMS-path). For these tests p values include a Bonferroni correction for six comparisons.

On 23 of the 160 scenarios (eight pilots, five scenarios, four displays), the pilot maneuvered to avoid a background aircraft before the designed conflict could occur. Although maneuver time data were lost for these events, the scenario was continued, and separation violations were considered in the analysis. For the purpose of comparing maneuver times between displays, timing data were only considered for 27 out of a possible 40 scenarios (eight pilots, five scenarios) where they were available for all displays.

The Analytic Hierarchy Process (AHP) was used to determine the strength of pilot preference for each display.[19] AHP uses comparison questions of each display pair combination to produce overall display rankings that sum to unity. These rankings indicate the magnitude, rather than simply the order of preference. The strength of one display over another can be obtained by dividing the respective rankings.

Performance Data

Figure 3 shows the mean separation violation percentages considered over the 48 conflicts per display. Reductions in separation violations for the three enhanced displays when compared to the TCAS display were not significant at the 95% confidence interval [TCAS and rate, $t(47) = 0.24$, $p > 0.05$; TCAS and commanded state $t(47) = 1.17$, $p > 0.05$; and TCAS and FMS-path, $t(47) = 1.71$, $p > 0.05$]. Although the results are not statistically significant, the apparent trend toward reduced separation violations with higher levels of intent is supported by previous experiments.[2–5] Several studies have concluded that straight line predictors, similar to the heading arrow provided in the rate display, are effective

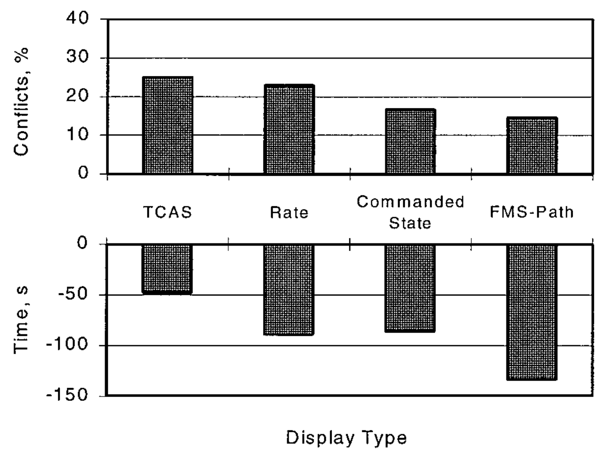

Fig. 3 Mean separation violation percentage (top) and mean maneuver time before projected separation violation (bottom) by display type.

in reducing traffic conflicts.[2–4] Johnson et al. found that predictor information in combination with a conflict probe enabled pilots to maintain a greater separation from conflicting traffic.[5]

The mean maneuver times shown in Fig. 3 indicate the remaining time before a separation violation would have occurred, if the pilot had not maneuvered. This prediction was based on the intruder's known track and the ownship velocity at the time the maneuver was initiated. Pilots maneuvered earliest with the FMS-path display, followed by the rate and commanded-state displays, and latest with the TCAS display. The maneuver time differences for the following display combinations were statistically significant at the 95% confidence interval ($p \leq 0.05$): TCAS and rate, $t(26) = 2.92$, $p = 0.043$; TCAS and FMS-path, $t(26) = 5.66$, $p < 0.001$; rate and FMS-path, $t(26) = 3.85$, $p = 0.004$; and commanded state and FMS-path, $t(26) = 4.02$, $p < 0.003$. Only a marginal significance level was observed between the TCAS and commanded-state displays: $t(26) = 2.61$, $p = 0.088$. Differences between the rate and commanded-state displays were not statistically significant: $t(26) = 0.870$, $p > 0.10$.

It is unlikely that the loss of maneuver time data when the subjects maneuvered to avoid background aircraft affected the observed trends. Of the 13 pilot/scenario combinations where timing data were lost for at least one display, six were from the long-range conflict, which produced the largest difference in maneuver time between displays. One point was lost from the intruder overtake scenario, and two points were lost in each of the remaining three scenarios. In related studies earlier maneuvering with prediction-enhanced displays has been reported by Hart and Loomis for straight- and curved-line predictors[3] and Johnson et al. for a straight-line predictor display with a conflict probe.[5]

Across all conditions where maneuver time data were available, a strong relationship was observed between the separation violation percentage and the maneuver time. Figure 4 shows the percentage of all conflicts resulting in lost separation for avoidance maneuvers that were conducted within various time intervals before a predicted separation violation. When pilots maneuvered within 20 s of the conflict, a separation violation occurred 83% of the time. The incidents of lost separation decreased monotonically as pilots allowed more time for the maneuver. Only 9% of maneuvers begun between 80 and 100 s before the conflict resulted in lost separation.

Preference Data

AHP rankings for each of the four displays are provided in Fig. 5. Pilots greatly preferred all of the intent displays to the TCAS display. The commanded-state display had the highest overall ranking, being preferred by pilots twice as much as the rate and FMS-path displays and nine times as much as the TCAS display.

Ratings of individual elements of intent information that scored at least a score of 4 (somewhat valuable) on a scale of 1 (very detrimental) to 5 (very valuable) included FMS-path (4.0), commanded altitude (4.3), current heading (4.5), and commanded heading (4.6). In contrast, 63% of the pilots found the FMS-path display to be too cluttered, as compared to only 13% for the commanded-state display and none for the TCAS or rate displays.

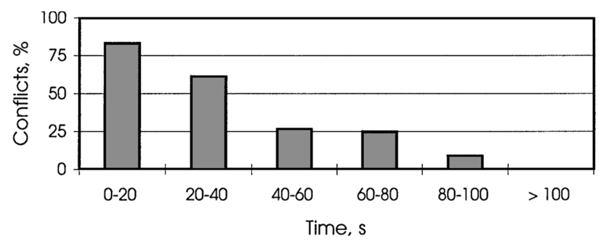

Fig. 4 Experiment 1 conflicts resulting in separation violation vs maneuver lead time interval.

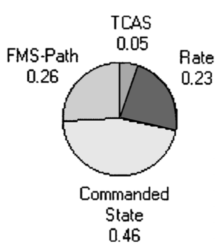

Fig. 5 Pilot display preference for Experiment 1.

Discussion

General results indicate that pilots maneuver earlier and have fewer separation violations when provided with some level of intent information. These trends have been well documented in prior studies that compared displays similar to the TCAS and rate displays used in this experiment.[2–5] Because the experiment did not reveal a significant improvement for the FMS-path display, it is interesting to take a closer look at the many practical issues involved with implementing such a display.

Incorporating an FMS-path display would require the consideration of many details neglected in this experiment. The displayed FMS trajectory and its associated conflict probe were simplified to a basic linear model, neglecting speed changes, mode transitions, and differences in FMS architecture between aircraft. Existing datalink systems may have limited carrying capacity to broadcast this information. Even assuming a perfect system model, changing or unexpected wind conditions will cause the intruder's FMS to adjust its initial path predictions. Such uncertainties may significantly affect the predicted location of long-range conflicts. Many questions also remain about a pilot's ability to use FMS-path information. Considering that numerous problems have been documented where pilots have become confused over the state of their own aircraft,[12] one could question whether they would be capable of monitoring and interpreting the states of other aircraft. FMS-path information would also not be available for non-FMS equipped aircraft or for those flying in the manual or state modes. These mixed mode operations were not considered in this experiment.

Pilots had substantially fewer separation violations when they initiated early avoidance maneuvers. This benefit, however, seems to be concentrated on maneuvers conducted within several minutes of the conflict. In this experiment pilots were always able to avoid a separation violation when they maneuvered at least 2 min before the conflict. Because the uncertainty in predicting aircraft position increases as the alert time increases, an excessively long alert time may lead to unnecessary maneuvers.[13,14] In actual flight operations the appropriate time to alert will likely depend on the phase of flight.

Above the TCAS level a pilot's maneuver time appeared to depend more on when the alert was issued than on the level of intent displayed to the pilot. Similar maneuver times were observed between the rate and commanded-state displays, which both used conflict probes based only on current velocity. The earlier maneuver times associated with the FMS-path display were likely caused by its conflict band appearing an average of 72 s earlier than the rate-based conflict band.

The results of the first experiment led to two key questions that warranted further study. First, which of the three additions to the TCAS display (intent information shown on the display, the conflict probe, or the profile-view display) were most responsible for the reduction in separation violations and earlier maneuvering? Also, would pilots perform as well with a display that alerts within several minutes of a conflict when compared to one that has a longer range alert?

Experiment 2: Application of Intent Information

Objective

The second experiment explored the individual and collective effect of different levels of displayed and applied intent information. The TCAS and commanded-state displays were tested as two levels of displayed intent information. The commanded-state display was chosen to represent the three enhanced displays from the first experiment because it led to similar performance, was preferred by the pilots, and would be easier to implement than the FMS-path display. Each display was tested with three conflict probe options: no conflict probe, a conflict probe with a 2-min look-ahead, and a long-range conflict probe.

Data from Experiment 1 suggested that maneuvering earlier, up to several minutes before the conflict, led to fewer separation violations. The 2-min and long-range conflict probes were included to test the hypothesis that maneuvering earlier than 2 min before the anticipated conflict would not lead to a further reduction in separation violations. For the 2-min version the conflict probe did not provide an alert until the ownship and intruder were within 2 min of a projected conflict. The look-ahead time of the long-range conflict probe was longer than any of the scenarios used during the experiment, causing a conflict band to appear as soon as a conflict was detected.

To compare pilot performance with and without a profile-view display, the commanded-state display from Experiment 1 was modified to include only a plan view. The intruder overtake scenario from Experiment 1 was used in Experiment 2 to allow for a direct comparison.

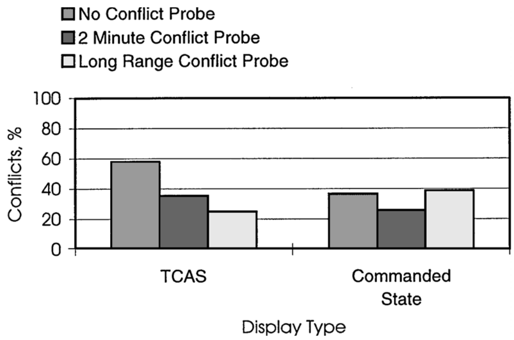

Fig. 6 Mean separation violation percentage by display option.

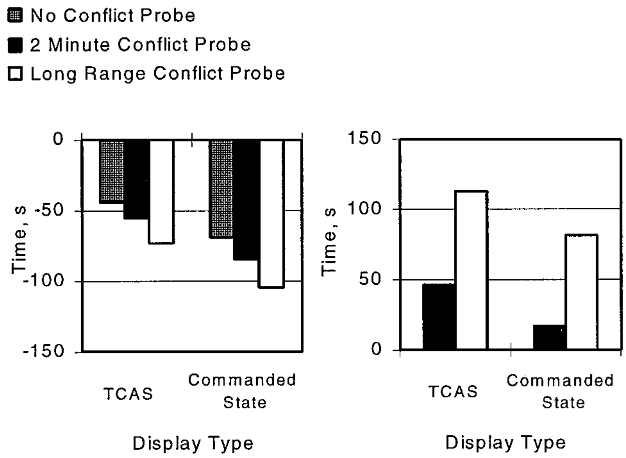

Fig. 7 Mean maneuver time before projected separation violation (left) and after conflict band appeared (right) by display option.

Displays

Various changes were made to the commanded-state display to make it compatible with a plan-view format and to ensure that automatic conflict prediction cues coincided with the activation of the conflict probe. The commanded altitude was shown in magenta text next to the traffic symbol. To suppress the alert until the predicted conflict was within the look-ahead time, displayed intent information was shown for all aircraft and could not be deselected. In addition, the aircraft ID and current heading arrow remained white until the conflict probe was activated.

Method

The experimental apparatus and procedure were identical to those used in Experiment 1.

Experimental Design

Experiment 2 incorporated a 2 Display by 3 Conflict Probe by 4 Scenario within-subjects factorial design counterbalanced for display and conflict probe order. The 2-min and long-range conflict probes were always presented consecutively, but were alternated evenly between displays. The postexperiment questionnaire asked pilots to rate the six display options and to give their opinion on the proper range and look-ahead time for the conflict probe.

Subjects

Eight commercial airline pilots served as volunteer test subjects. Six were active, and two had retired within the preceding four months. All had experience on glass cockpit aircraft. Their flight experience ranged between 8,300 and 28,000 h with a mean of 16,225 h. Their ages ranged from 35 to 60 with a mean of 49.

Scenarios

Experiment 2 scenarios included a short-range conflict, long-range conflict, intruder overtake, and one where the intruder maneuvered in response to the subject pilot's maneuver, creating a more serious conflict. With the exception of the conflict-causing aircraft on the maneuvering intruder scenario, all intruders had preprogrammed flight paths independent of the subject pilot's actions. As in Experiment 1, scenarios were designed to be difficult and were mirror imaged.

Results

Data Analysis

The occurrence of separation violations and pilot maneuver time were again used as the primary performance parameters. Separation violation data concentrated on differences between all display options and the basic TCAS display, in addition to comparisons of the 2-min and long-range conflict probes for the TCAS and commanded-state displays. These results were analyzed with McNemar tests with a one-tailed t test. Provided p values include a Bonferroni correction for seven comparisons. Maneuver times before a predicted separation violation were analyzed with a three-way analysis of variance (ANOVA) for repeated measures.

On nine of the 192 possible conflicts (two displays, three conflict probe options, four scenarios, eight pilots), the subject pilot maneuvered to avoid a background aircraft before the designed conflict could occur, and maneuver time data were lost. The nine missing points were restricted to one pilot, which enabled the ANOVA to be performed on the remaining seven pilots. As in Experiment 1, separation violation data was considered for all conflicts.

Preference data was analyzed with the AHP. Rankings are provided for the TCAS and commanded-state displays, with and without a conflict probe.

Performance Data

The mean percentage of separation violations, considered over the 32 conflicts per display option, is shown in Fig. 6. The addition of either a conflict probe or intent information to the basic TCAS display resulted in fewer separation violations. Display options producing a statistically significant reduction in separation violations when compared with the basic TCAS display included the TCAS with 2-min conflict probe, $t(31) = 2.99$, $p = 0.02$; TCAS with long-range conflict probe, $t(31) = 3.81$, $p = 0.002$; commanded-state with no conflict probe, $t(31) = 2.99$, $p = 0.02$; and commanded-state with 2-min conflict probe, $t(31) = 3.81$, $p = 0.002$. Only a marginal difference was observed between the basic TCAS and the commanded-state with long-range conflict probe displays: $t(31) = 2.28$, $p = 0.10$. The differences between the 2-min and long-range conflict probes for the TCAS, $t(31) = 1.38$, $p > 0.10$ and commanded-state displays, $t(31) = 1.46$, $p > 0.10$ were not statistically significant.

Figure 7 shows the mean maneuver times for seven pilots and the associated 28 conflicts by display option. It provides the time remaining before a predicted separation violation and the elapsed time after a conflict band appeared. The ANOVA performed on maneuver lead time revealed statistically significant main effects for display type, $F(1, 6) = 7.85$, $p = 0.03$, and conflict probe option, $F(2, 12) = 6.51$, $p = 0.01$. Very little interaction occurred between displays and conflict probe options, $F(2, 12) = 0.17$, $p = 0.84$. Adding displayed intent information to the TCAS display did not affect the relative maneuver lead times between conflict probe options, but did reduce the time to maneuver after a conflict band appeared. With the 2-min conflict probe pilots maneuvered 47 s

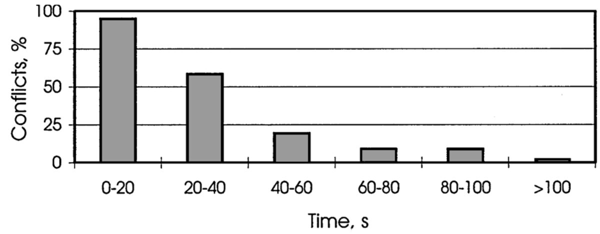

Fig. 8 Experiment 2 conflicts resulting in separation violation vs maneuver lead time interval.

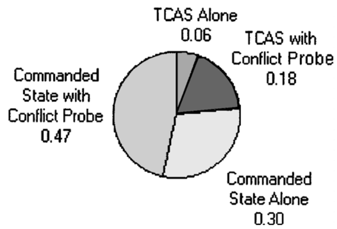

Fig. 9 Pilot display preference for Experiment 2.

after the conflict band appeared when using the TCAS display and only 17 s after with the commanded-state display. This difference is statistically significant: $t(27) = 2.42$, $p = 0.02$.

Figure 8 shows the relationship between the separation violation percentage and the maneuver lead time. It considers all conflicts where maneuver time data were available and is an analogous representation to Fig. 4 for Experiment 1. Consistent with Experiment 1, separation violations were reduced substantially when pilots allowed more time for the avoidance maneuver. As before, the most significant improvement occurred for maneuvers conducted within 2 min of the conflict.

To compare performance with and without the profile-view display, a limited comparison of separation violation percentage was made between the commanded-state display of Experiment 1 (with profile view) and the commanded-state display with 2-min and long-range conflict probes of Experiment 2 (without profile view). Considered over eight pilots for each case, this scenario resulted in three separation violations with the profile-view display in Experiment 1. In Experiment 2, two separation violations occurred with the 2-min conflict probe, and three occurred with the long-range conflict probe. Considering the similarity in separation violations with this scenario, the profile-view display did not appear to significantly affect pilot performance.

Preference Data

The AHP rankings, shown in Fig. 9, indicate that pilots preferred all display options over the basic TCAS display by at least a 3:1 margin. They tended to prefer the commanded-state display with a conflict probe the most, but if required to make a choice, they would rather have intent information shown directly on the display than incorporated into a conflict probe.

Fifty percent of the pilots found the commanded-state display to be too cluttered with the conflict probe, and 25% found it too cluttered if alone. Problems with overlaid symbology and intent information shown for nonconflicting aircraft were mentioned. Compared to Experiment 1, the higher percentage of pilots mentioning clutter on the commanded-state display was likely related to their inability to turn off the information. Nonetheless, pilots gave value ratings of 4.4, 4.6, and 4.9 (on a 5-point scale) to the current heading, commanded heading, and commanded altitude, respectively.

Discussion

Separation violations were reduced by almost the same amount over the basic TCAS display when intent information was either displayed directly or incorporated into a conflict probe. When displayed intent and a conflict probe were used in combination, there was little improvement in separation violations over cases where they were provided individually although pilots maneuvered earlier and preferred the commanded-state display with a conflict probe.

As with Experiment 1, there were fewer separation violations when pilots maneuvered earlier, up to several minutes before the conflict. The addition of either displayed intent or a conflict probe both led to earlier maneuvers. Pilots responded more rapidly to the 2-min conflict probe when using the commanded-state display. Commanded-state information may reinforce the issuance of an alert, thus reassuring pilots that an avoidance maneuver is appropriate.

Separation violation percentages were similar between the 2-min and long-range conflict probes. For the conflicts used in this experiment, there seemed to be no additional benefit to alerting to conflicts beyond 2 min. Pilots may have felt that the long-range conflict probe was issued too early, as they maneuvered more promptly in response to the 2-min conflict probe.

A more in-depth study of the profile-view display is warranted. Work by Merwin et al.[11] and Ellis et al.[10] showed that pilots are more effective at interpreting vertical information when provided with a three-dimensional display. Many pilots indicated that they did not include the profile-view display in their scan, suggesting that it may become more useful with further practice.

Discussion

Results from the two experiments show that intent information is valuable in enabling pilots to recognize and resolve traffic conflicts. Displaying intent directly or incorporating it into a conflict probe both appear to be beneficial. With intent in either form, pilots maneuvered earlier and had fewer separation violations. Also, pilots rated all intent displays higher than the baseline TCAS display.

The commanded-state display led to the best overall performance on the two experiments. In Experiment 1 pilots performed as well with the commanded-state display as they did with the other intent displays and better than with the TCAS display. The commanded-state display was preferred by the pilots and would be more practical to implement than the FMS-path display. Pilots consistently gave high ratings to the current heading, commanded heading, and commanded altitude. These opinions were shared by pilots in an experiment by Johnson et al.[5] In that study several pilots identified commanded heading and altitude as desirable items to add to a rate-enhanced display.

A pilot's ability to use various intent levels may depend on the phase of flight in which the display is used. The high traffic density and crew workload associated with terminal area operations may suggest a simpler intent level. Most pilots indicated that the FMS-path display was too cluttered, suggesting that this information may be difficult to interpret in a high workload situation. Also, the climb and descent phases are most likely to have the complicated vertical path transitions that lead to the FMS-path prediction problems already mentioned. On the contrary, crews have more time available during cruise flight, and conflicts are likely to be limited to a single airplane. Consideration of a limited number of waypoints, in addition to the presence of simpler vertical trajectories, may make it possible for pilots and automated systems to adequately predict conflicts based on FMS path. Knowledge of an intruder's downstream course change would be beneficial if it allows a pilot to plan ahead and perform a more efficient avoidance maneuver.

In addition to the flight phase, the rules of operation will likely influence the design of future traffic displays. As part of the FAA Free Flight effort, work on procedures that assign priority to conflicting aircraft is being done in parallel with systems development projects. Pilots may benefit from displays that clearly indicate the aircraft having the right of way and whether the ownship pilot must initiate an avoidance maneuver. Without this information pilots may maneuver unnecessarily when given priority.[20] Eurocontrol is developing a set of Extended Flight Rules that assign priority based on encounter geometry, phase of flight, and flight status.[21] As part of these rules, the lower priority aircraft must execute an avoidance maneuver at a minimum distance from the projected conflict. If implemented, these rules would strongly influence the conflict probe look-ahead time.

A 2-min look-ahead time for a conflict probe appeared to be sufficient in alerting pilots to conflicts in these two experiments. In Experiment 2 pilots performed as well with the 2-min conflict probe as they did with the long-range version. Also, most of the reduction in separation violations occurred for maneuvers performed within 2 min of the conflict. Because few, if any, separation violations occurred for the long-range conflicts in these and similar experiments,[5,20] future studies could investigate a crew's ability to make smaller, more efficient maneuvers when provided with long-range alerts.

Conclusion

The use of intent information in future traffic displays will depend greatly on the structure of a continually evolving air-traffic management system. Traffic displays will need to provide pilots with information that allows them to manage conflicts safely and efficiently while respecting limitations in system architecture and pilot workload. These two experiments have shown, however, that pilots are supportive of intent information and are able to use it effectively in a variety of traffic situations.

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