Experimental Studies of the Effect of Intent Information on Cockpit Traffic Displays

by

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1

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ABSTRACT

Intent information provides knowledge of another aircraft's current and future trajectory states. Prototype traffic displays were designed for four different levels of intent: Position, Rate, Commanded State, and FMS-Path. The current TCAS Display, which shows altitude rate in addition to current position and altitude, was used as a baseline and represents the lowest level of intent. The Rate, Commanded State, and FMS-Path Displays show increasing levels of intent information using TCAS-like symbology in addition to incorporating a conflict probe and profile view display. An initial experiment was run on the MIT Part Task Flight Simulator in which eight airline pilots flew five traffic scenarios with each of the four displays. Results show that pilots had fewer separation violations and maneuvered earlier with the three intent displays. Separation violations were reduced when pilots maneuvered earlier. A second experiment was run to compare performance between displaying intent information directly and incorporating it into a conflict probe. A different set of eight airline pilots flew four traffic scenarios with the TCAS and Commanded State Displays with and without the conflict probe. Conflict probes with two minute and long range look-ahead times were tested. Displaying conflict bands or showing intent information directly both led to fewer separation violations and earlier avoidance maneuvers than the base TCAS Display. Performance was similar between the two minute and long range look-ahead conflict probes. Pilots preferred all intent displays over the TCAS Display.

Thesis Supervisor: R. John Hansman
Title: Professor of Aeronautics and Astronautics

3

Acknowledgments

Table of Contents

List of Figures

List of Tables

List of Acronyms

AHP	Analytic Hierarchy Process
ANOVA	Analysis of Variance
ASL	Aeronautical Systems Laboratory
ATC	Air Traffic Control
CDTI	Cockpit Display of Traffic Information
CDU	Control Display Unit
EHSI	Electronic Horizontal Situation Indicator
FAA	Federal Aviation Administration
FMS	Flight Management System
LNAV	Lateral Navigation
MCP	Mode Control Panel
MIT	Massachusetts Institute of Technology
PFD	Primary Flight Display
RA	Resolution Advisory
RTCA	Radio Technical Commision for Aeronautics
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
TA	Traffic Advisory
T/C	Top of Climb
TCAS	Traffic Alert and Collision Avoidance System
T/D	Top of Descent
VNAV	Vertical Navigation
VOR	Very High Frequency Omnidirectional Range

Chapter 1

Introduction

In the early 1980's, significant work was done toward the development of a Cockpit Display of Traffic Information (CDTI). Many experiments showed that predictor information added to intruder airplane symbols aided pilots in determining the future position of those aircraft (Palmer et. al, 1980 and Palmer, 1983). However, the traffic display used in conjunction with the Traffic Alert and Collision Avoidance System (TCAS) in today's commercial aircraft shows only the current position, altitude, and altitude rate of intruder aircraft. TCAS alerts pilots to potential conflicts by issuing a Traffic Alert (TA) or a more serious Resolution Advisory (RA), which includes a command to climb or descend. The TCAS system functions well in the current airspace system, in part because its primary function is to supplement and compensate for errors by Air Traffic Control (ATC).

With the possible transition to a more unstructured air traffic management system underway, the CDTI may take on a more active role (RTCA Technical Report, 1995). Pilots may eventually be given more liberty in choosing their own routes, but could incur more responsibility for maintaining separation from other traffic (FAA Technical Report, 1995). To make informed decisions about potential conflicts, pilots would likely need to know more information about the intruder's future position than is provided by the current TCAS system. This information, known as "aircraft intent", exists at many different levels, with higher levels representing a more complete knowledge of the other aircraft's intended trajectory.

By showing only current position, altitude, and altitude rate, the current TCAS system represents a low level of intent information. A somewhat higher level adds horizontal rate information, such as current airspeed and heading. With rate and position information, a linear prediction of an aircraft's future position can be made. This prediction becomes invalid, however, as soon as the aircraft changes velocity. To more accurately predict position, information about an intruder's autopilot states can be considered. For example, knowing the first target state would

provide the roll-out heading or level-off altitude, if maneuvering. These elements are known as the commanded heading and commanded altitude, respectively. An even higher intent level would consider multiple future trajectory states. Obtaining an intruder's flight plan programmed into its Flight Management System (FMS) would allow its position to be predicted even after several changes of state. Flight plan information could include the location and crossing altitude of future waypoints.

Figure 1.1 shows several intruder trajectory segments, drawn in order of increasing level of intent. The lowest intent level depicted is the *Position Level*, which shows the aircraft's current position and its altitude of 20,000 ft. The *Rate Level* shows the intruder's current heading and indicates that it is descending. The level of intent provided by the current TCAS System falls between the *Position* and *Rate Levels*, since TCAS shows the altitude rate but does not provide horizontal rate information. At the *First Target State Level*, next commanded state information is added to the information available at the *Rate Level*. The intruder's commanded heading is represented by the dashed arrow. In addition, its next level-off altitude of 17,000 ft. is known. The highest level of intent shown is the *Trajectory Level*, which adds information about multiple future states. This level shows the location and crossing altitude of upcoming waypoints. The intruder will cross Waypoint A at 17,000 ft., and then turn to Waypoint B, where it will cross at 15,000 ft.

Increasing Levels of Intent ⟶

Position

20000

Rate

20000
↓

First Target State

20000
↓
17000

Trajectory

17000
A

20000

15000
B
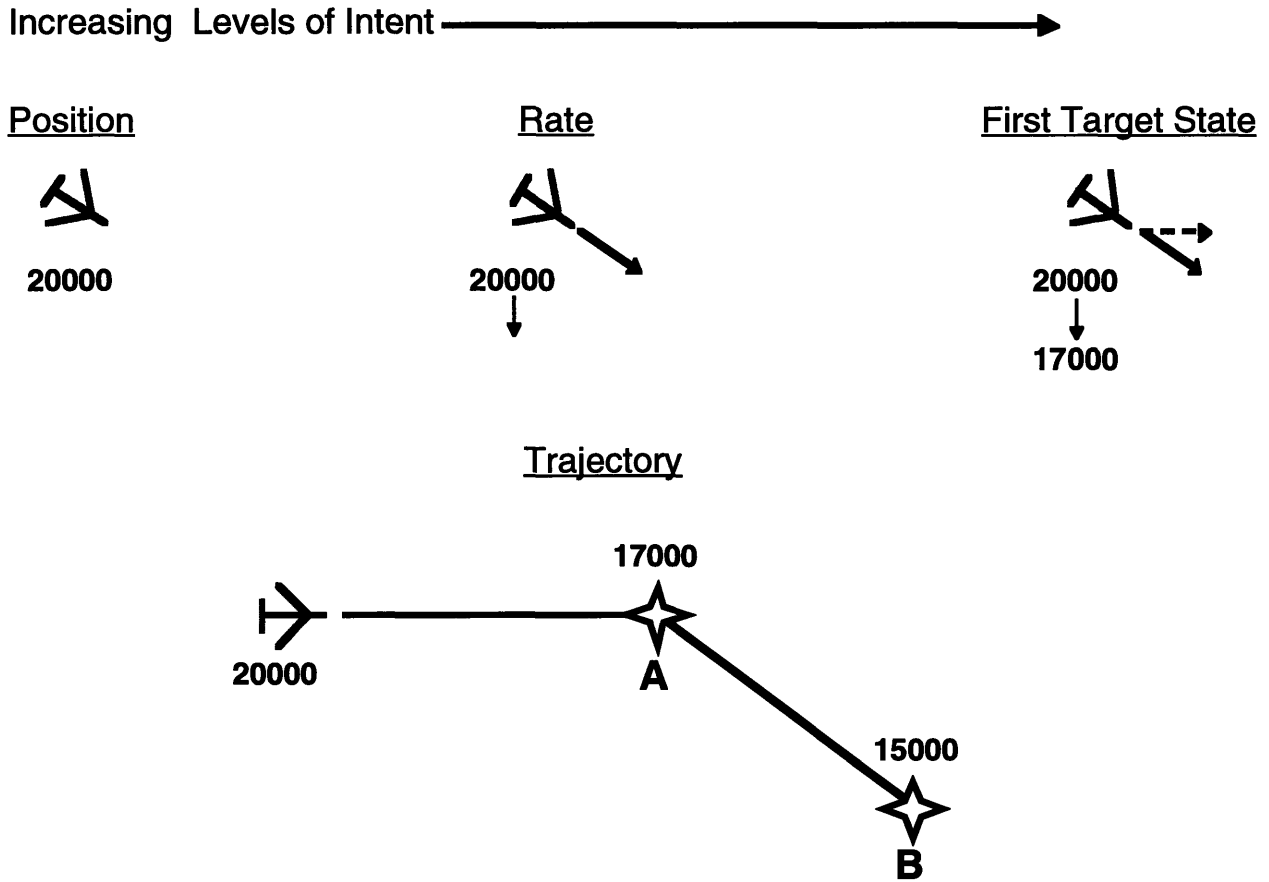
Figure 1.1: Intruder Trajectory Segments Showing Different Levels of Intent Information

Actual implementation of the intent levels discussed above depends on several factors. Among prominent limitations are the capability of air to air datalink systems used to exchange the information and the operating mode of intruder aircraft.

Any intent information incorporated into a CDTI would likely be communicated via an air to air datalink system. One form of datalink, the Mode S transponder, sends and receives information in small data packets called squitters. TCAS equipped aircraft identify each other by exchanging unique addresses through the Mode S squitter. Current squitters only have room to carry these Mode S addresses. The MIT Lincoln Laboratory has conducted tests on extended squitters which allow position and altitude to be exchanged (Orlando, Knittel, and Boisvert, 1994). Additional developments will likely be required before higher levels of intent information can be accessed.

The amount of information available at a given time also depends on the operating mode of the intruder aircraft. Available information can be examined by considering the block diagram of Figure 1.2, which shows the available modes and the pilot/aircraft interface.
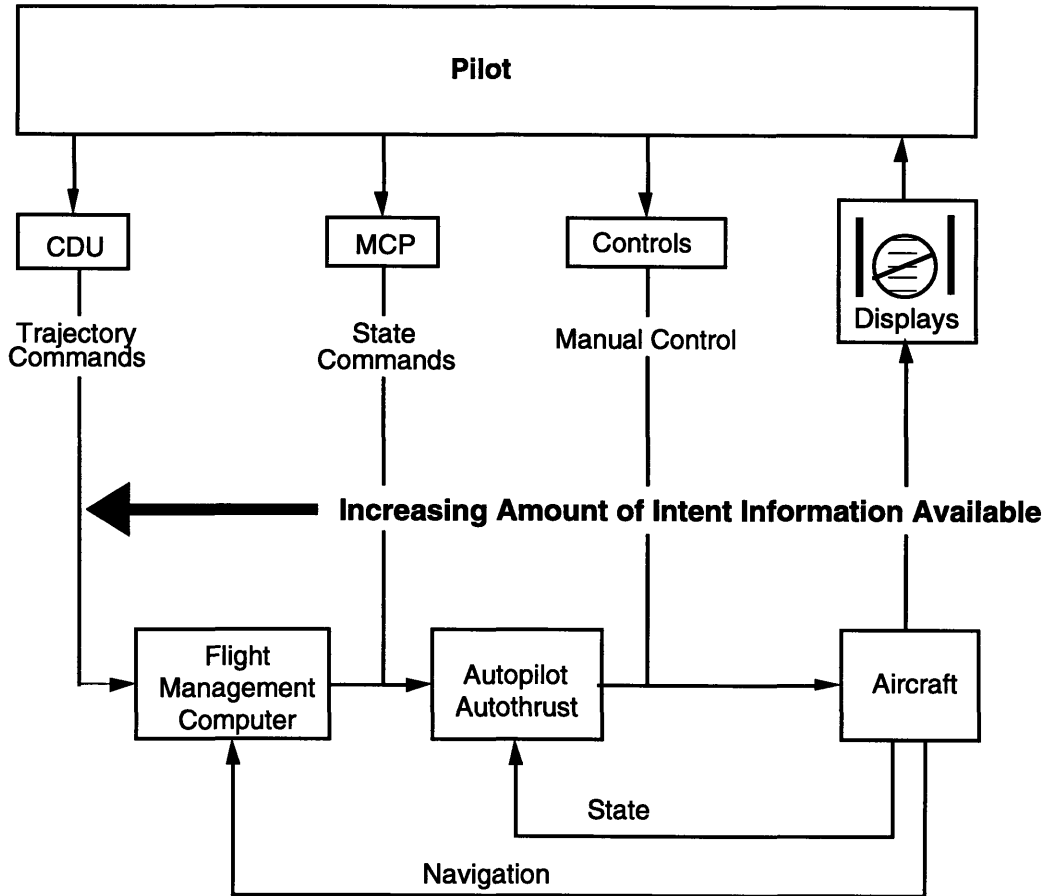
Figure 1.2: Aircraft Mode Diagram

The pilot interacts with the aircraft through three primary modes: manual, state, and trajectory. Each level involves the pilot issuing a command to the aircraft and receiving feedback about the aircraft states through various displays. With each additional outer loop, the pilot communicates more intentions about future states to his own aircraft. Since this information is available, it can be passed to other aircraft, assuming a capable datalink system.

Manual control, the innermost control loop, is the simplest mode because the pilot bypasses the autopilot and commands the aircraft directly with the flight controls. While in manual mode,

the intent information available includes only 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 (MCP). The autopilot will make the necessary control inputs to achieve the desired state. In this mode, both the aircraft's current and commanded state variables are available, representing a higher level of intent. For instance, an aircraft may currently be climbing through 17,500 ft. with a command to level-off at 18,000 ft. The current altitude is 17,500 ft. and the commanded altitude is 18,000 ft.

The outermost loop is the trajectory mode. At this level, the pilot interacts with a Control Display Unit (CDU) 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) will determine where climbs and descents should begin and where speed changes should occur in order to achieve the desired trajectory.

Several levels of intent information were selected for study in an exploratory experiment. Intent levels were chosen to correspond to information available in each of the three control modes. The *Rate Level* corresponds to the Manual Mode and incorporates information about an aircraft's current state. The *Commanded State Level* adds first target state commands to the current state variables available at the Rate Level. The *FMS-Path Level*, which represents the Trajectory Mode, includes information about the FMS programmed Lateral (LNAV) and Vertical (VNAV) Navigation paths. Additionally, the current *TCAS System* was used as a baseline, and represents the lowest level of intent information.

Chapter 2

Experiment 1

An exploratory experiment was conducted to determine whether intent information could improve pilots' ability to resolve traffic conflicts. The relative benefit between the four different levels of intent described in Chapter 1 was considered. To evaluate pilots' ability to use intent information, prototype displays were developed corresponding to each intent level discussed in Chapter 1. It was assumed that the specified level of intent information would always be available.

As shown in the test matrix of Table 2.1, subject pilots flew five different traffic scenarios with each of the four prototype displays.

Table 2.1: Experiment 1 Test Matrix

Levels of Intent Information

Conflict Scenarios		TCAS	Rate	Commanded State	FMS-Path
	1 Intruder Overtake	X	X	X	X
	2 Intruder Trajectory Change	X	X	X	X
	3 Ownship Overtake	X	X	X	X
	4 Long Range Conflict and Intruder Level-Off	X	X	X	X
	5 Dual Conflict	X	X	X	X

The primary objective of the scenarios was to maintain a safe distance from other traffic. Scenarios were designed to represent common traffic situations. Lateral, vertical, and combined lateral/vertical conflict geometries in addition to single and multiple aircraft conflicts were tested. An intruder level-off safely above the subject pilot's aircraft was also considered.

The two independent variables tested were the level of intent information and the scenario type. The matrix was counterbalanced by varying the order in which displays were presented to the pilots. Design of the displays and scenarios is described below.

2.1 Display Design

Prototype displays were designed for the TCAS, Rate, Commanded State, and FMS-Path levels of intent. The primary goal of the display design process was to provide a clear picture of the traffic situation using the specified level of intent information. The following functional requirements were established for the design of each display: show the specified level of intent, identify intruder aircraft that are a potential threat and indicate the level of threat, and show where a minimum separation will be violated.

Each traffic display is superimposed onto an Electronic Horizontal Situation Indicator (EHSI), based on the Boeing format and color conventions. The ownship is drawn as a white triangle at the bottom of the display. Navigation aids are shown in cyan and the ownship heading bug is represented by a dashed magenta line. Intruder aircraft and navigation fixes move relative to the stationary ownship symbol. Each display uses current TCAS symbology to represent the position and relative altitude of intruder aircraft. In addition, the TCAS climb or descent arrow is shown if an intruder is climbing or descending at least 500 fpm. TCAS II logic, including traffic advisories and resolution advisories, is available on all prototype displays.

2.1.1 TCAS Display

The current TCAS Display is used as the baseline intent display. Figure 2.1 shows a sample TCAS Display. The intruder aircraft is represented by the open white diamond. An up arrow is drawn between the traffic symbol and the aircraft ID, indicating a climb rate of at least 500 fpm. In Figure 2.1, the intruder's altitude is 700 feet 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.
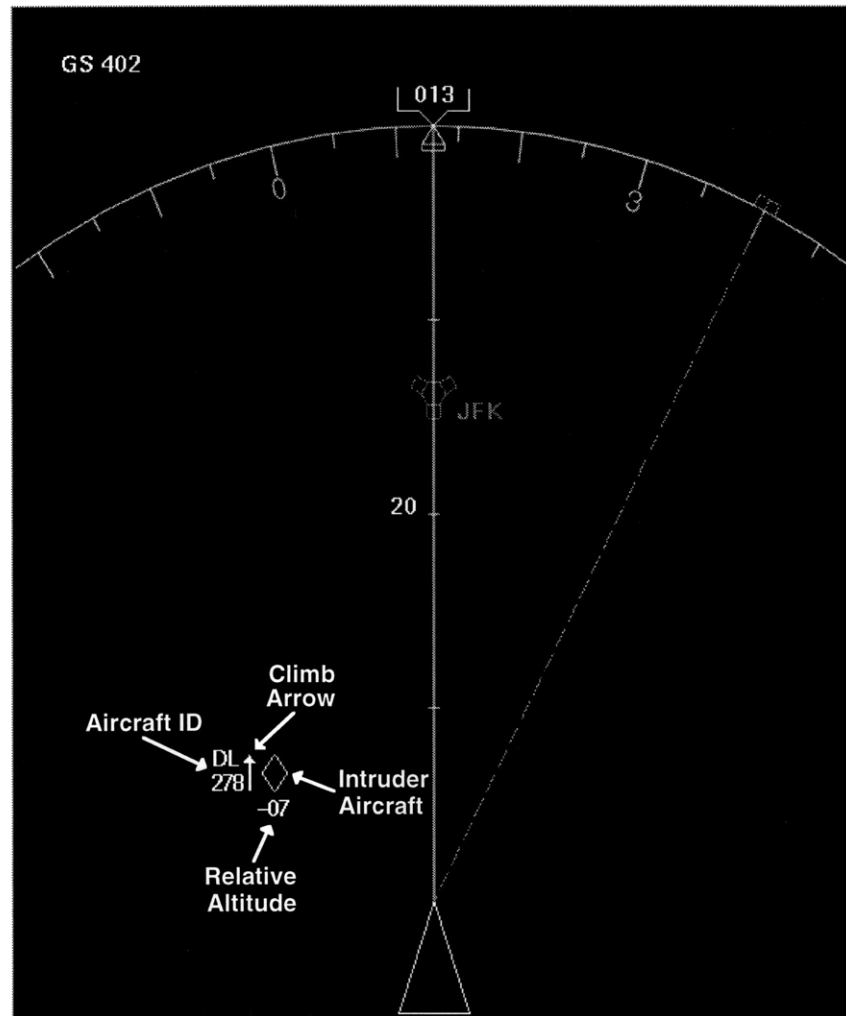
Figure 2.1: TCAS Display

2.1.2 Rate Display

The Rate Display incorporates three major additions to the TCAS Display: rate information shown on the display, a conflict probe, and a profile view display. A sample Rate Display is given in Figure 2.2.

The intruder's heading is represented by a short arrow drawn from the center of the traffic symbol. The heading arrow is drawn in the direction of the intruder's absolute heading. Since the EHSI uses the current position of the ownship as the origin of the display, the intruder will not necessarily appear to move in the same direction as its heading arrow. The absolute heading was found to present a more intuitive picture of an aircraft's flight direction than its heading relative to

GS 402

013

0   3

20

Conflict Band

Current
Aircraft ID   Heading

DL
278   -07

Altitude (ft)

20 000

19 000

18 000   Ownship   Conflict Band

Altitude Rate
DL
278   Ownship
Velocity Vector

17 000

0   10   20   30

Distance Along Flight Path (nm)
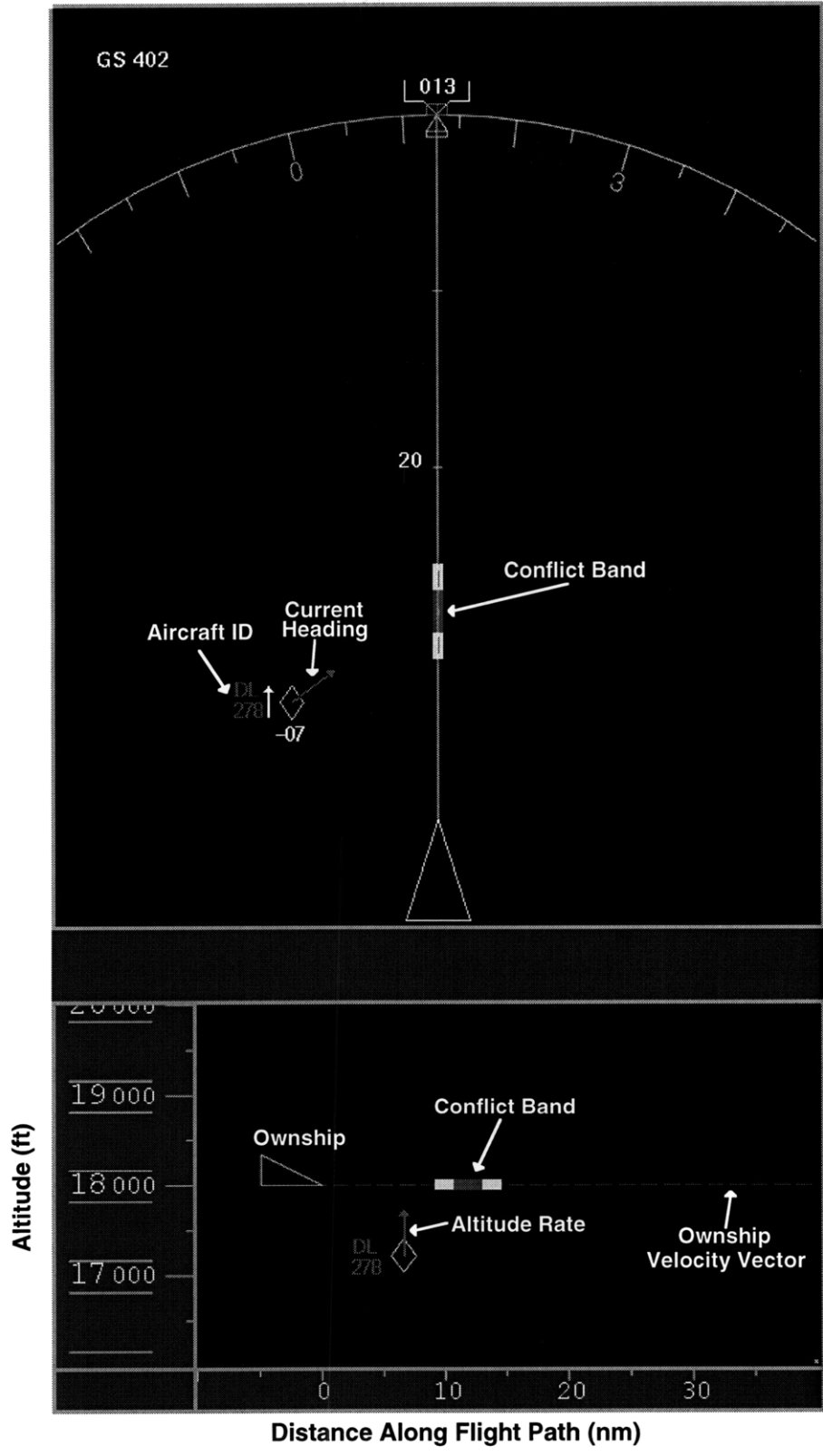
Figure 2.2: Rate Display

the ownship. When navaids are shown on the EHSI, a pilot can use the absolute heading to compare an intruder's direction of flight with fixed spatial coordinates. This comparison is especially valuable when either aircraft is maneuvering.

A conflict probe linearly extrapolates the ownship and intruder trajectories to determine whether defined separation criteria will be violated. Consistent with the level of intent, the probe assumes a constant airspeed, heading, and vertical speed for both aircraft. A yellow caution zone is drawn if an intruder is projected to be within 3 nm. laterally and 700 ft. vertically of the ownship. Likewise, if the spacing is projected to be within 2 nm. laterally and 500 ft. vertically, a red warning zone is drawn. Caution and warning zones are shown as a conflict band drawn on the ownship flight path, where the two aircraft will be within the indicated spacing. If a conflict is predicted for more than one aircraft, the conflict bands will superimpose, with red always overwriting yellow. When the ownship or intruder maneuver, the shape and location of the conflict band change, giving an indication of whether the maneuver is improving or deteriorating the situation. Once the conflict band disappears, the ownship pilot is assured that separation will be maintained, absent any further maneuvering by either aircraft.

As an additional part of the conflict probe, the color of both the heading arrow and the aircraft ID are changed to indicate the intruder's level of threat. White is used if there is no conflict, yellow if a caution zone is predicted, and red if a warning zone is predicted. This convention is used to make it easier to identify which aircraft is causing the threat indicated by the conflict band.

A profile view display is also provided to help enhance the pilot's understanding of the traffic situation in the vertical plane. The display is based on a prototype Electronic Vertical Situation Display designed to improve pilots' situation awareness of vertical autoflight mode transitions (Vakil, Midkiff, and Hansman, 1996). The horizontal axis is the distance along the ownship's flight path and the vertical axis is the absolute altitude. The distance ahead of the ownship shown on the profile display corresponds to the range on the EHSI. A dashed magenta arrow represents the ownship's vertical velocity vector. The TCAS traffic symbol and aircraft ID

26

are shown on the display. Using the same criteria as the TCAS Display, a climb/descent arrow is drawn from the center of the symbol if the altitude rate exceeds 500 fpm. The aircraft ID and the climb/descent arrow are colored to indicate the level of threat. Since any position along a line perpendicular to the ownship flight path represents a single point on the display's horizontal axis, it is not unusual to have multiple airplane symbols merge together. For this reason, only those aircraft projected to cause a conflict with the ownship are shown on the profile display.

2.1.3 Commanded State Display

The Commanded State Display adds the intruder's commanded heading and altitude, if maneuvering, to the information shown on the Rate Display. A sample Commanded State Display is provided in Figure 2.3.

If an intruder aircraft is turning, the commanded heading is shown with a magenta arrow. The current heading will appear to sweep toward the commanded heading until the aircraft rolls out of the turn, at which point the commanded heading arrow will disappear. A magenta arrow was selected to be consistent with the Boeing color scheme for showing commanded state information. If an intruder projected to cause a conflict is climbing or descending, its commanded altitude is shown as a short magenta line on the profile view display. A yellow or red arrow, consistent with the level of threat, is drawn from the airplane symbol to the commanded altitude.

GS 402

013

0

3

20

Conflict Band

Current
Heading

Aircraft ID

DL
278

-07

Commanded
Heading

Commanded
Altitude

Conflict Band

Ownship

DL
278

Ownship
Velocity Vector

Altitude (ft)

20 000

19 000

18 000

17 000

0   10   20   30

Distance Along Flight Path (nm)
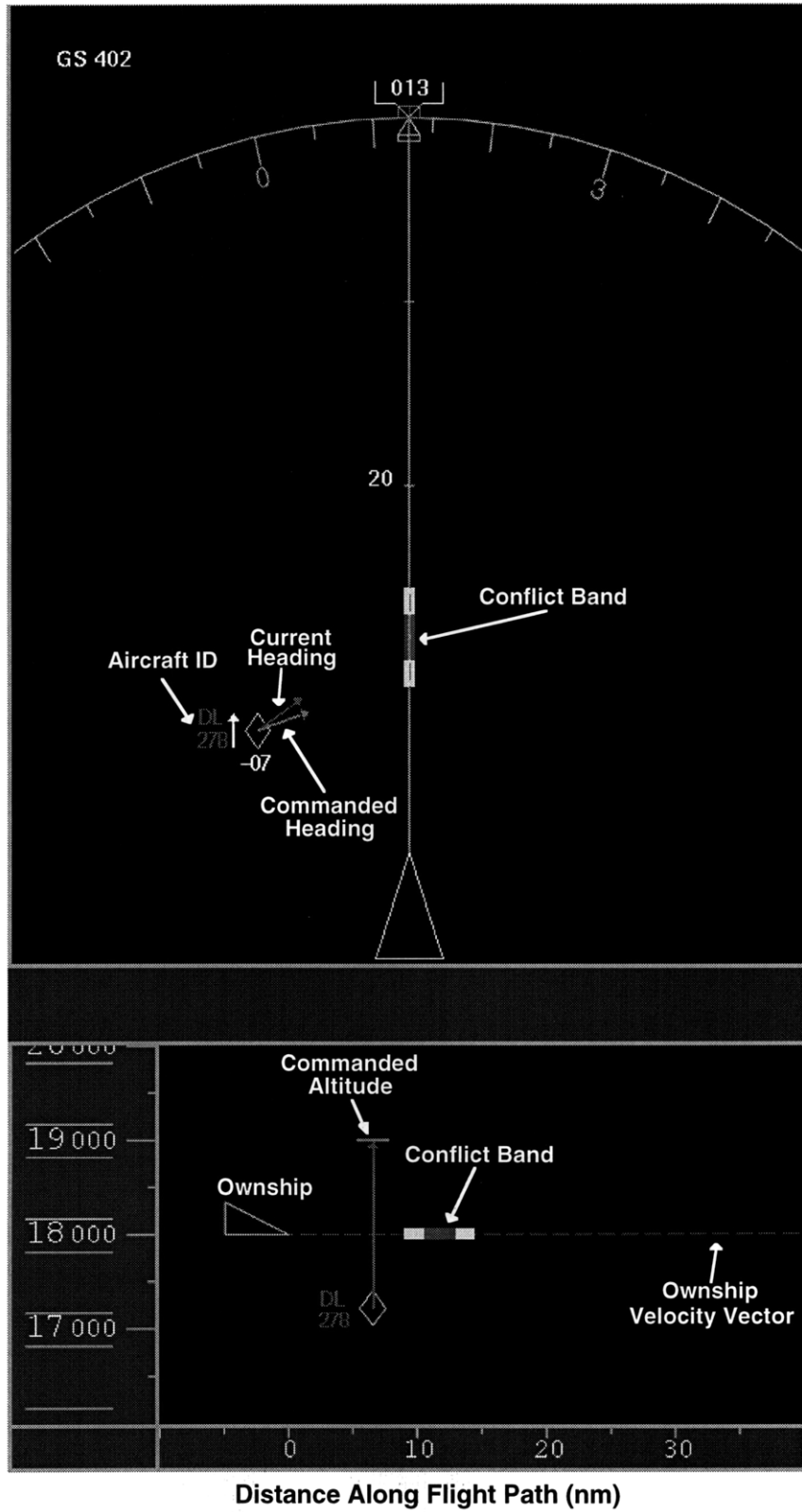
Figure 2.3: Commanded State Display

28

Conflict prediction is performed in the same way as the Rate Display, by considering the ownship and intruder's current airspeed, heading, and vertical speed. Commanded state information is not considered because it could cause a developing conflict to be suppressed based on an intruder's intended actions. An example of such a situation is shown in Figure 2.4.
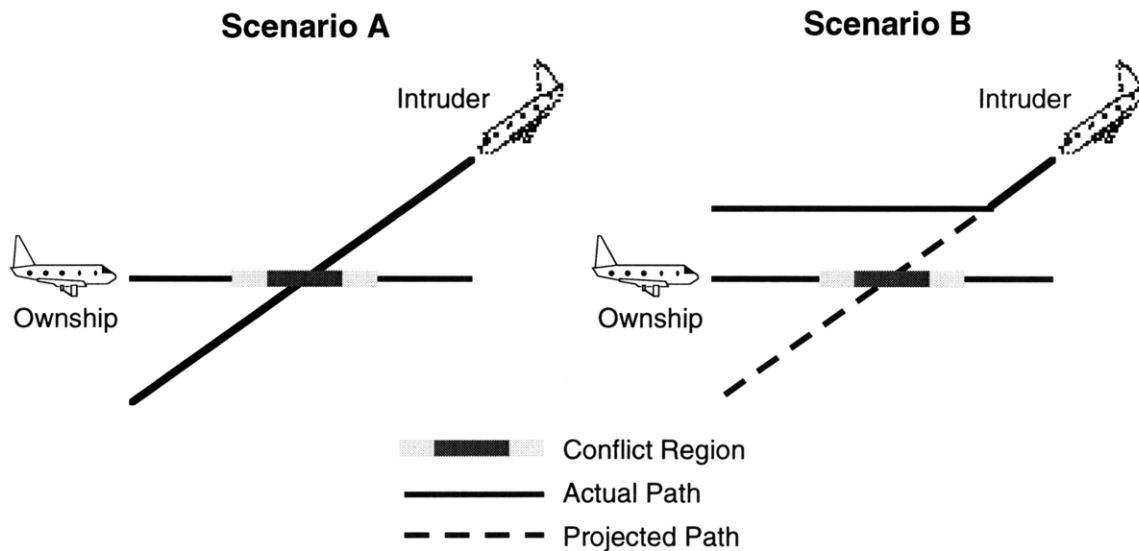
Figure 2.4: Sample Conflict Scenarios

The ownship is flying to the right at constant altitude and the intruder is descending. In both scenarios, a conflict is predicted based on current state information. In Scenario A, the intruder maintains a constant vertical speed through the ownship's altitude, and the conflict occurs as predicted. In Scenario B, the intruder levels off safely above the ownship, as indicated by its commanded altitude. In this case, the conflict band would not disappear until the intruder starts to level-off.

2.1.4   FMS-Path Display

The FMS-Path Display adds an intruder's programmed trajectory, including Lateral Navigation (LNAV) and Vertical Navigation (VNAV) path information, to the TCAS Display. A sample display is shown in Figure 2.5. LNAV waypoints are shown with the conventional
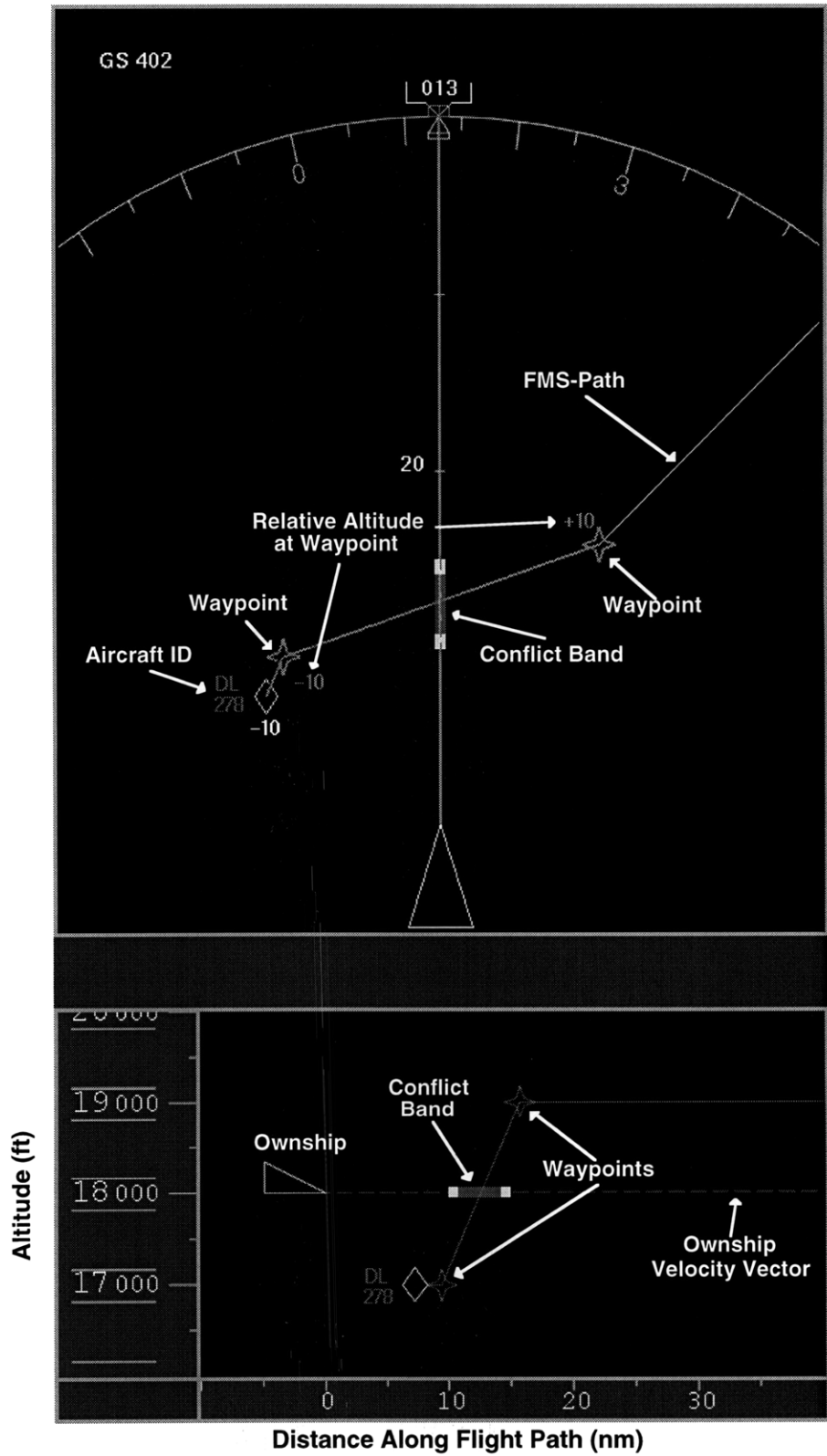
Figure 2.5: FMS-Path Display

waypoint symbol and are connected by magenta lines, originating at the intruder aircraft symbol. This depiction is consistent with the ownship LNAV path shown on Boeing EHSI's. VNAV crossing altitudes at each waypoint are incorporated into the display by showing the projected relative altitude between the intruder and ownship when the intruder reaches the waypoint. The projection is based on the ownship's current vertical speed and the assumption that the intruder will cross the waypoint at the crossing altitude.

The vertical path for intruder aircraft projected to cause a conflict is shown on the profile view display. The waypoint symbols are drawn at their distances along the ownship flight path and at the absolute crossing altitude.

Conflicts are predicted in two different ways. One method uses only the intruder's current state information, as is done for the Rate and Commanded State Displays. Conflicts are also predicted by considering the intruder's LNAV/VNAV path information. If either method predicts a conflict, a conflict band is drawn. If an intruder has multiple waypoints that cross the ownship's path, only its nearest conflict is shown. As with the Commanded State Display, the conflict probe takes a conservative approach and does not suppress alerts based on an intruder's future intentions.

An example of the two methods in which conflicts are predicted for the FMS-Path Display is shown in Figure 2.6. The conflict in Scenario A is predicted based on current state information. Even though the intruder plans to turn away, it would cause a conflict based on its current heading. In Scenario B, the intruder's FMS-Path indicates that a conflict will occur after the next waypoint.

31

Scenario A   **Scenario B**

Intruder   Ownship   Intruder   Ownship

■ Conflict Region

—— Actual Path

– – – – Projected Path
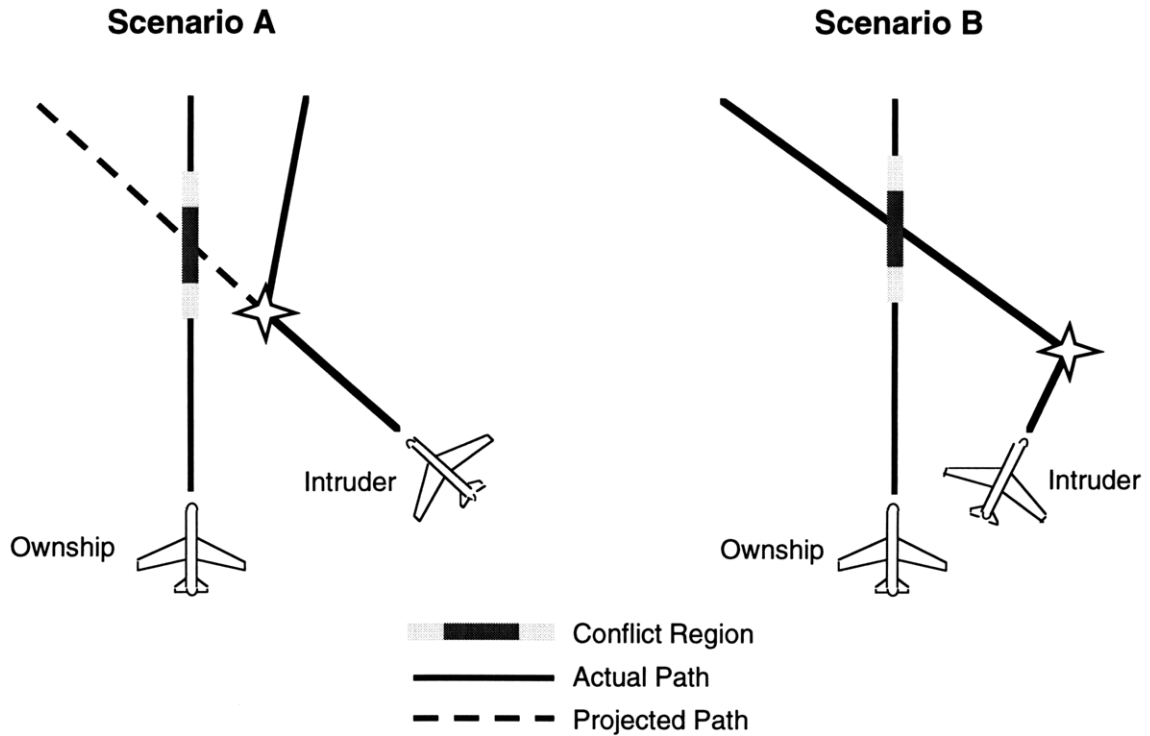
Figure 2.6: Sample FMS-Path Conflict Scenarios

To perform the conflict prediction based on the FMS-Path, several simplifying assumptions had to be made about the intruder's operating mode and its actual trajectory. It was assumed that all aircraft were flying in LNAV/VNAV path mode, therefore ensuring that the FMS-Path was always available. Most trajectory assumptions were related to the VNAV Path. The vertical profile is very difficult to predict precisely because it depends on uncertain environmental factors and differences in FMS architecture between aircraft.

Most flight management systems use models of wind and temperature profiles to predict when the aircraft will reach its next altitude in a climb (Top of Climb or T/C) and where a descent needs to begin to make a crossing altitude at a downline waypoint (Top of Descent or T/D). As the aircraft flies along, a change in forecasted wind or temperature conditions will change the location of the T/C and/or T/D. The vertical profile can also change if the aircraft encounters unforecasted conditions while climbing or descending. In a climb, this difference would affect the location of the T/C. In a descent, the aircraft could miss the crossing altitude if an unexpected tailwind is encountered.

Differences in FMS architecture between aircraft also limit the ability to accurately predict the VNAV Path. For example, in a high speed descent, an aircraft may be unable to meet both a speed and an altitude restriction at the next waypoint. Some aircraft may reduce speed and fail to reach the crossing altitude, while others may meet the altitude restriction and wait to reduce speed until after passing the waypoint. Constructing a model that could accurately represent situations such as these for many different aircraft would be very difficult.

To manage these issues, a simplified deterministic path between waypoints was assumed. Uncertainties in the location of the T/C and T/D were eliminated by assuming the intruder would maintain a constant vertical speed between waypoints, effectively putting the T/C at the next waypoint and the T/D at the previous waypoint. Figure 2.7 shows the range of possible real trajectories compared to the assumed trajectory.
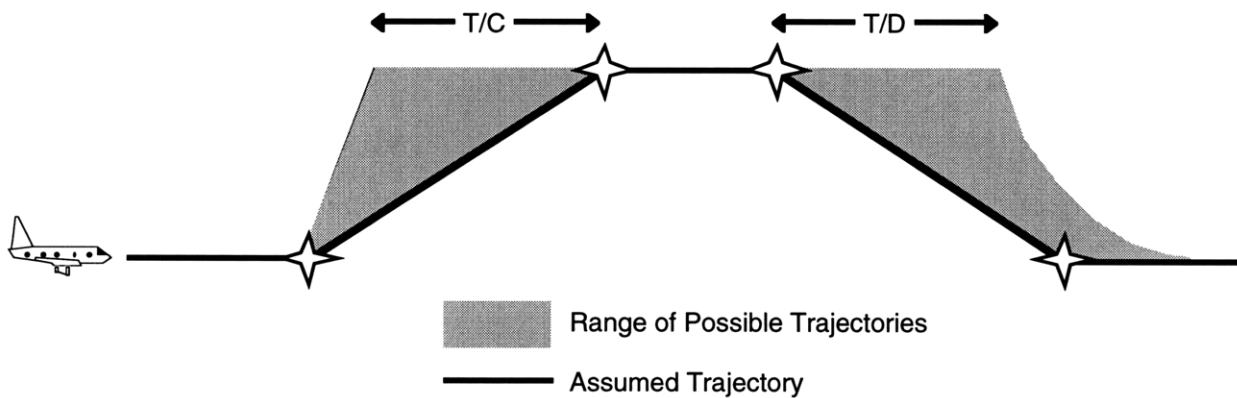
Figure 2.7: Comparison of Range of Possible Trajectories with Assumed Trajectory

The descent profile is curved to show the possible overshoot that can occur if the aircraft is unable to make the crossing altitude. Secondly, it was assumed that the intruder would maintain a constant speed throughout the trajectory. This eliminated the need to consider the many possible acceleration or deceleration tactics that could be used. Finally, a linear trajectory was assumed for level-offs and turns between waypoints. This was done to mitigate the differences in flight dynamics between aircraft.

2.2   Scenario Design

Five scenarios were designed to represent common traffic situations. To keep the subject from focusing only on the conflict causing airplane, several background aircraft were included in each scenario. Scenario design was done on an ATC simulator, developed as part of a study on remote situation generation (Johnson & Hansman, 1995). The ATC simulator is an interactive tool for designing trajectories for multiple intruder aircraft. A sample of the display screen is given in Figure 2.8.
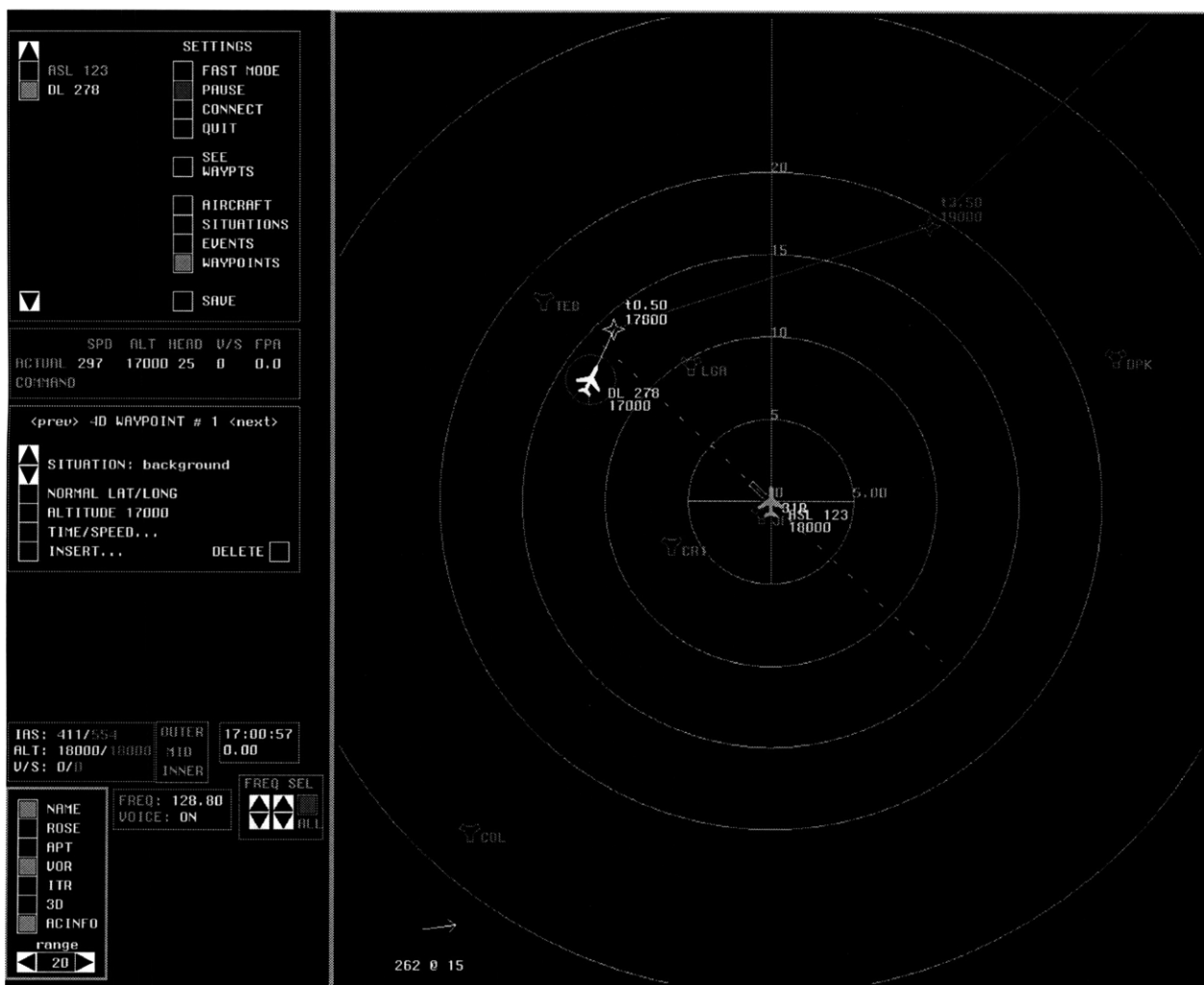
Figure 2.8: ATC Simulator Screen

The simulator allows the user to select 4D trajectories for the intruder aircraft. The location, altitude, and time of arrival at the waypoint are selected. Performance constraints such as maximum speed, climb, and descent rates are employed to prevent unrealistic intruder trajectories. Intruders fly at constant vertical speed between the waypoints, which also serve as the T/C and T/D. These trajectories are consistent with the assumptions made for the FMS-Path Display.

2.2.1 Scenario 1: Intruder Overtake

The Intruder Overtake Scenario was developed as a strictly vertical conflict. The scenario also tested pilots' ability to recognize a conflict from behind. It was thought that pilots may have trouble interpreting the intruder's flight path, which overlaps the ownship path. As shown in Figure 2.9, the intruder starts directly behind and 4000 ft. above the ownship. It overtakes the ownship and descends through the ownship altitude, causing a separation violation one minute, 22 seconds (1:22) after the start of the scenario.
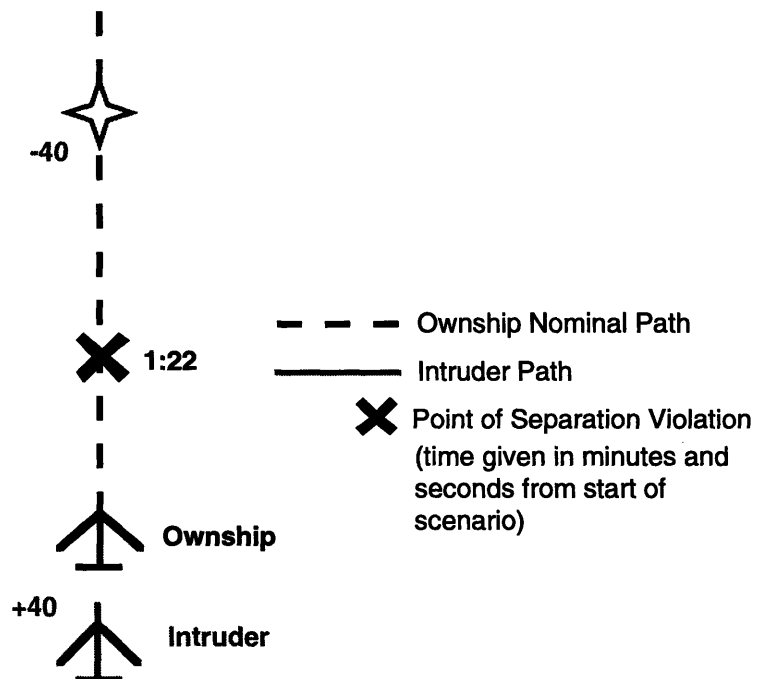
Figure 2.9: Intruder Overtake Scenario

2.2.2 Scenario 2: Intruder Trajectory Change

In this scenario, the intruder has an original trajectory that will take it away from the ownship. At 1:30, the intruder changes a waypoint to the other side of the ownship flight path, creating a co-altitude conflict. The trajectory change occurs one minute before its arrival at the turn-in waypoint. A conflict band is issued as soon as the trajectory change is initiated on the FMS-Path Display, but not until the intruder turns into the subject on the Rate and Commanded State Displays. A schematic is provided in Figure 2.10.
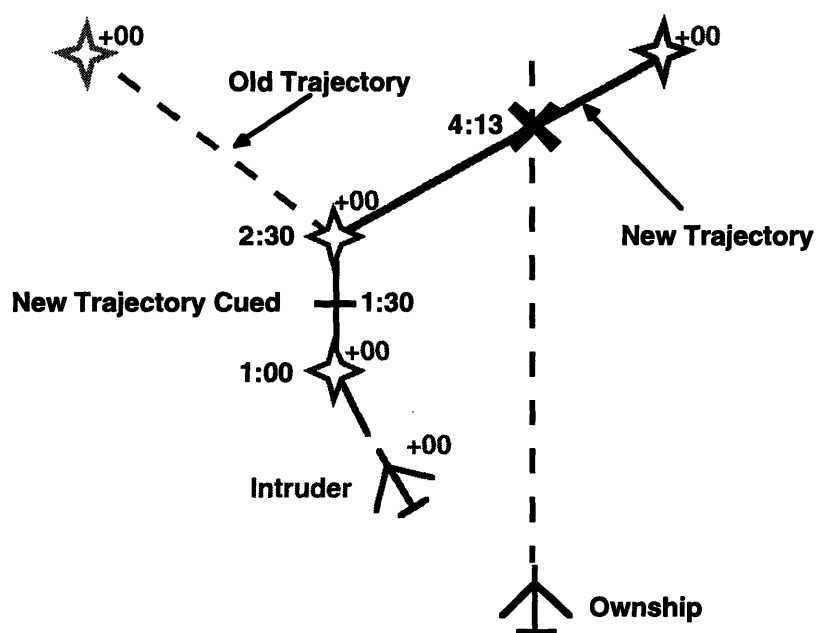
Figure 2.10: Intruder Trajectory Change Scenario

2.2.3 Scenario 3: Ownship Overtake

As shown in Figure 2.11, the geometry of this conflict is similar to that of the Intruder Overtake in Scenario 1. The two aircraft eventually fly on the same flight path, with the intruder climbing through the ownship's altitude. The intruder starts 2000 feet lower and does not climb until it turns onto the ownship flight path. The faster ownship has caught up by the time the intruder reaches the ownship altitude.
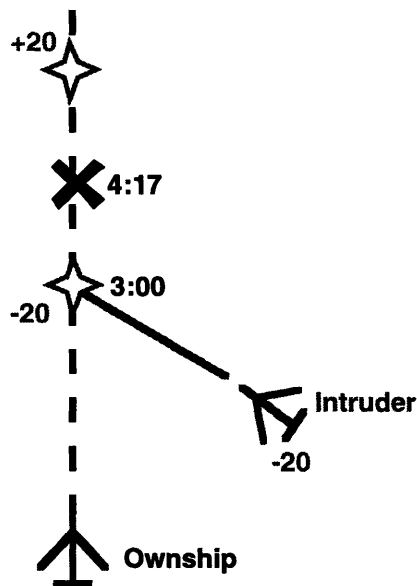
Figure 2.11: Ownship Overtake Scenario

2.2.4 Scenario 4: Long Range Conflict and Intruder Level-Off

This scenario, shown in Figure 2.12, involves two distinct events, a long range co-altitude conflict and an intruder that appears to create a conflict, but levels off safely 1000 ft. above the ownship. The long range conflict was developed to see how pilots would use intent information in a situation where they had enough time to plan a maneuver strategy. Of particular interest was whether pilots would maneuver as soon as the conflict band appeared for the intent displays. This conflict is a co-altitude convergence that occurs 45 miles ahead of the ownship when the intruder turns into the ownship flight path.
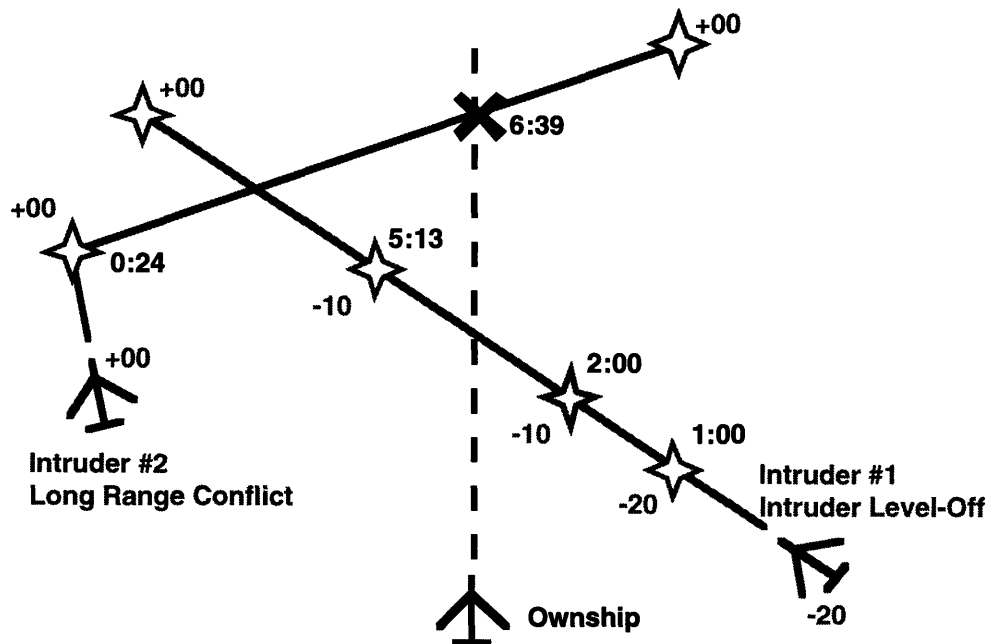
Figure 2.12: Long Range Conflict and Intruder Level-Off Scenario

An intruder level-off safely above the ownship's altitude was constructed to see whether pilots would rely on intent information indicating a safe level-off or would maneuver in response to a conflict band based on current state information. For all intent displays, a conflict band appears after the intruder begins the descent and disappears when the intruder commences the level-off.

2.2.5 Scenario 5: Dual Conflict

The dual conflict shown in Figure 2.13 involves two converging intruders descending and climbing through the ownship's flight path.
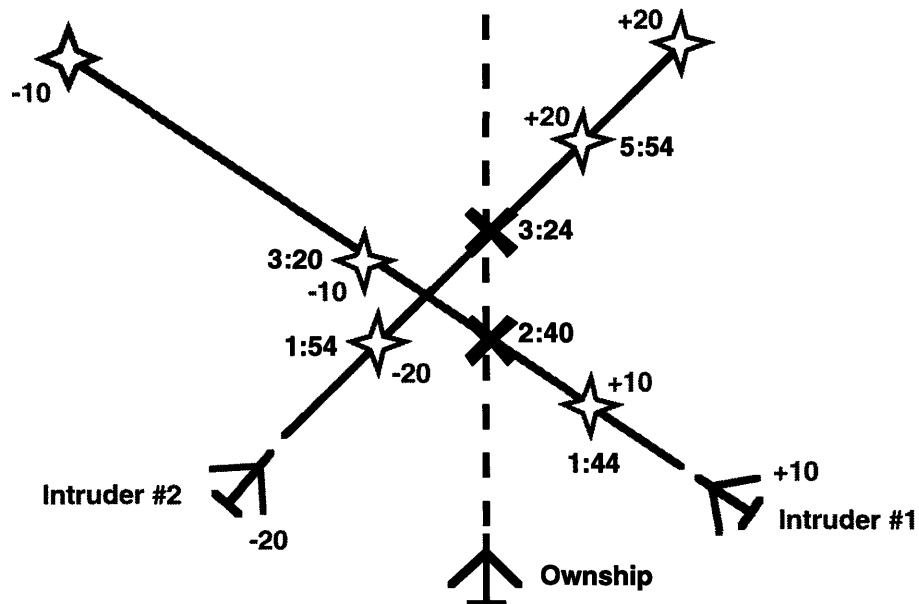
Figure 2.13: Dual Conflict Scenario

Of particular interest in this scenario was whether pilots could evaluate the extra information provided with the intent displays in a more complicated situation.

2.2.6 Use of Repeated Scenarios

To reduce the possibility that a pilot would recognize a scenario after repeated trials, scenarios were mirror imaged both laterally and vertically to produce four different scenario groups. The location and altitude of intruder aircraft and their waypoints were kept symmetric with respect to the original ownship flight path and altitude. Both the conflict causing aircraft and the background traffic were adjusted. An example group of mirror imaged scenarios is shown in Figure 2.14.
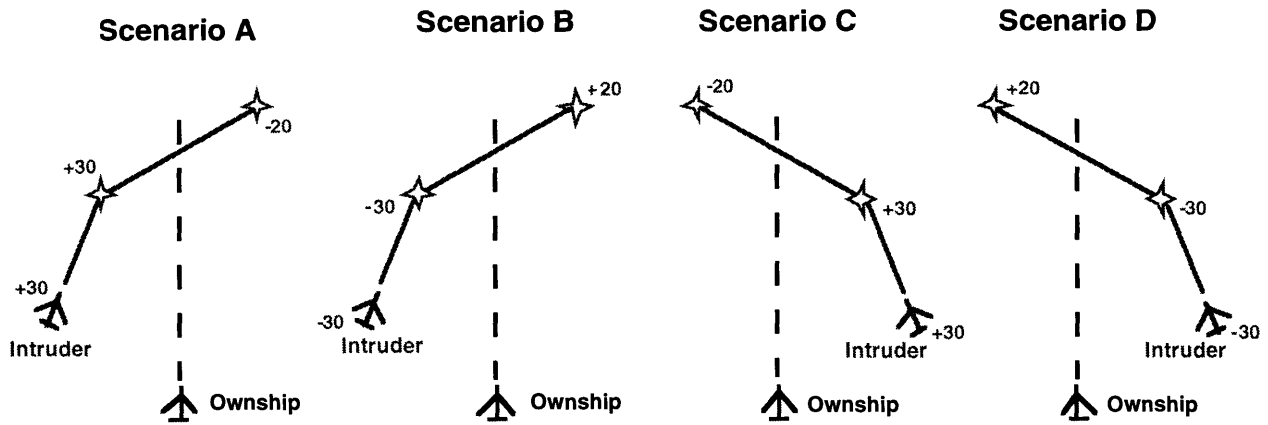
Figure 2.14: Mirror Imaged Scenarios

Scenario combinations A/B and C/D are mirrored vertically, and A/C and B/D are mirrored laterally.

2.3   Method

2.3.1   Apparatus

The experiment to test the four prototype traffic displays and the five scenarios was conducted on the MIT Part-Task Flight Simulator, located in the Aeronautical Systems Laboratory (ASL). Aside from the difference in traffic displays, the simulator setup was identical for each experimental run. A Silicon Graphics computer was used to fly the intruder aircraft through their preprogrammed trajectories and to show a Primary Flight Display and the traffic enhanced EHSI to the pilot. Subject pilots could use the autopilot or a side-stick to control the ownship.

A sample display screen is shown in Figure 2.15.
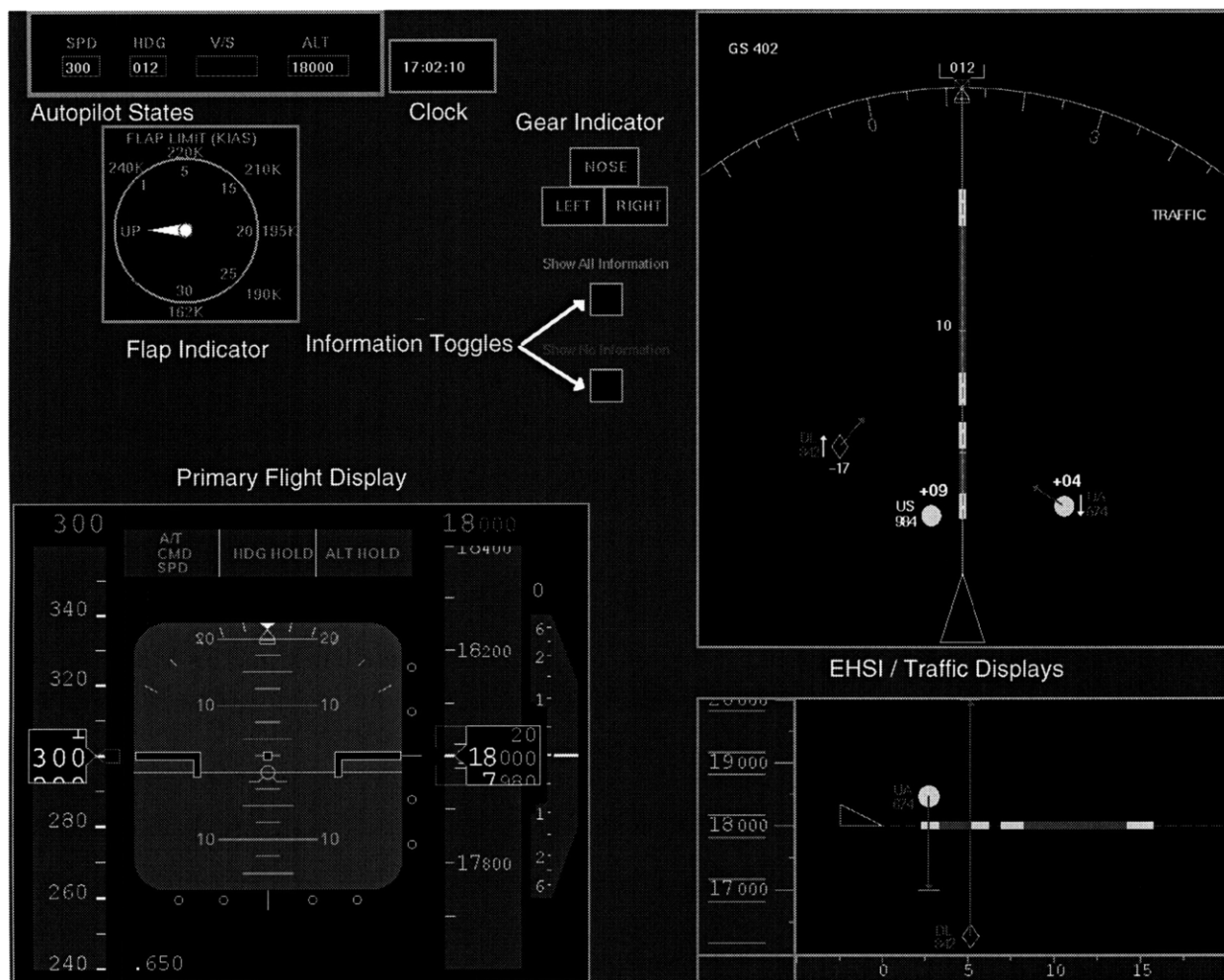
Figure 2.15: Pilot Display Screen

The Primary Flight Display (PFD), modeled after a B-747-400, is placed on the left side of the screen. The current autopilot modes are printed in green, above the attitude indicator. Speed and altitude tapes are shown on the left and right sides of the display, respectively. At the far right of the PFD, a vertical speed tape is provided. Commanded states dialed into the MCP are shown in magenta above the speed and altitude tapes, in addition to on a separate box at the top of the display screen. Flap and gear position indicators are shown, but were not used during the experiment. The EHSI/traffic display is placed on the right side of the screen. Figure 2.15 shows the Commanded State Display being run with Scenario 5, the Dual Conflict.

In an effort to reduce display clutter, intent information on the Rate, Commanded State, and FMS-Path Displays was initially suppressed if there was no predicted conflict. Pilots had the option to request or suppress this information for a particular airplane by clicking the computer mouse on the airplane symbol. Information for all airplanes could be displayed or suppressed simultaneously by clicking on the "Show All Information" or "Show No Information" boxes to the left of the traffic display. Information for airplanes projected to cause a conflict was always shown.

Pilots used keyboard buttons to increase or decrease the range on the display. For displays incorporating plan and profile views, the forward range was the same on each view and was adjusted simultaneously. Separate buttons were available to adjust the profile view's vertical range. There were no minimum or maximum range limits.

Autopilot control was accomplished through a Mode Control Panel (MCP), which had heading hold, heading select, altitude hold, vertical speed, and level change modes available. Buttons on the side-stick were used to disengage or re-engage the autopilot. The side-stick was used for manual control.

2.3.2   Procedure

The primary task of each scenario was the pilot's ability to maintain a minimum safe separation from other traffic, defined to be 2 nm. laterally or 500 ft. vertically. To see how pilots

could use intent information to resolve conflicts, the scenarios took place in an unstructured Air Traffic Control (ATC) environment. Pilots were entirely responsible for maintaining their own traffic separation and were free to conduct an avoidance maneuver of their choice at any time. A secondary objective was to arrive at a terminal area VOR as quickly as possible without increasing the aircraft's speed, and to make the minimum amount of course deviations necessary to meet the required traffic separation.

Scenarios began with the pilot flying toward the destination VOR at 18,000 ft. After maneuvering to avoid a conflict, pilots were instructed to turn back to the VOR and return to 18,000 ft. as quickly as possible, consistent with safety. The destination VOR was the only navigation aid shown on the EHSI.

In addition to maneuvering to avoid traffic conflicts, pilots were asked to identify intruder aircraft that presented a potential threat. This identification was made if the subject pilot perceived a threat that he felt could require an avoidance maneuver. When a pilot perceived such a threat, he would push a button on the sidestick.

2.3.3 Training

Prior to beginning the experiment, subject pilots were given a briefing covering the flight environment, simulator, and the required tasks. A sample briefing is given in Appendix A. Since a primary goal of the experiment was to determine how pilots could use both intent and TCAS information to resolve conflicts, the briefing emphasized that pilots were not restricted to current TCAS procedures such as performing a vertical maneuver after an RA is issued. Instead, pilots were asked to consider all of the information presented on the display and given by TCAS commands when deciding how and when to maneuver.

During the briefing, features of the primary flight display, TCAS traffic display, and mode control panel were explained in detail. Pilots were given several practice scenarios to become accustomed to the displays and the handling characteristics of the simulator. While running these scenarios, pilots were given the opportunity to fly with both the autopilot and the side-stick.

Practice was given with the base TCAS Display and then with the first display used in the experiment. During the experiment, practice scenarios were given before testing a display that included new information.

2.3.4 Performance Metrics

The primary objective performance metrics were the number of separation violations and the time in which the pilot conducted an avoidance maneuver. The time before separation violation and the time after a conflict band appeared (on displays employing a conflict probe) were considered.

At the end of the experiment, subject pilots filled out a questionnaire, asking them to rate the displays and elements of intent information and to describe their strategies for avoiding traffic conflicts. A sample questionnaire is provided in Appendix B.

2.3.5 Data Analysis

Within subjects paired t-tests were used to test for significance between means of both the separation violation percentage and the avoidance maneuver time. Since each subject was given all display and scenario combinations, paired t-tests were able to account for differences in performance between pilots. Error bars on all graphs represent one standard error.

Subjective display ratings were analyzed using the Analytic Hierarchy Process (Yang and Hansman, 1995). To perform the AHP, subjects were asked to give a preference rating for each possible display combination. A sample comparison question is provided in Figure 2.16.

TCAS Display   **Rate Display**

+20   +20

   absolutely   much   better   slightly   same   slightly   better   much   absolutely
   better   better   better   better   better   better
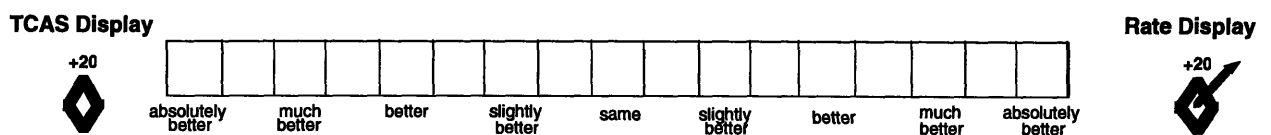
Figure 2.16: Sample Display Preference Question

This question asks subjects to give their preference between the Rate and TCAS Displays. If a subject prefers the Rate Display, a check is placed to the right of the middle "same" box.

Likewise, if the TCAS Display is preferred, a check is placed to the left of the "same" box. Stronger preferences are indicated by checking a box further from the middle. Comparison questions for each display pair are combined to produce overall rankings for each display. The sum of the overall rankings is normalized to 1. The overall rankings can then be represented as areas on a pie chart. The relative preference between two display options can be determined by dividing their respective pie chart areas.

2.4   Results

2.4.1   Subjects

Eight current commercial airline pilots from major US carriers served as volunteer subject pilots in the experiment. All had experience in "glass cockpit" and TCAS equipped airplanes. Their flight time ranged between 5,000 and 24,000 hours, with a mean of 10,875 hours and their age varied from 39 to 53, with a mean of 46. Four of the eight pilots were captains and six had military flying experience.

2.4.2   Objective Results: Overall

The first results to be presented are those that are averaged across all scenarios. Of primary importance are the occurrence of separation violations (cases where the subject pilot came within 2 nm. laterally or 500 ft. vertically of another aircraft) and the time in which the subject pilot initiated an avoidance maneuver. Plots of separation violation percentage and maneuver time vs. display type for individual scenarios are provided in Appendix C.

Separation violations are considered to be the most important performance metric, since the ultimate goal of a traffic display is to keep pilots safely separated from other aircraft. Figure 2.17 shows the percentage of all conflicts that resulted in a separation violation as a function of display type. Separation violations with background aircraft were included. The eight pilots flew six conflicts per display, leading to a total of 48 conflicts per display. One should note that the scenarios were designed to be difficult so that differences in performance between displays could be detected.
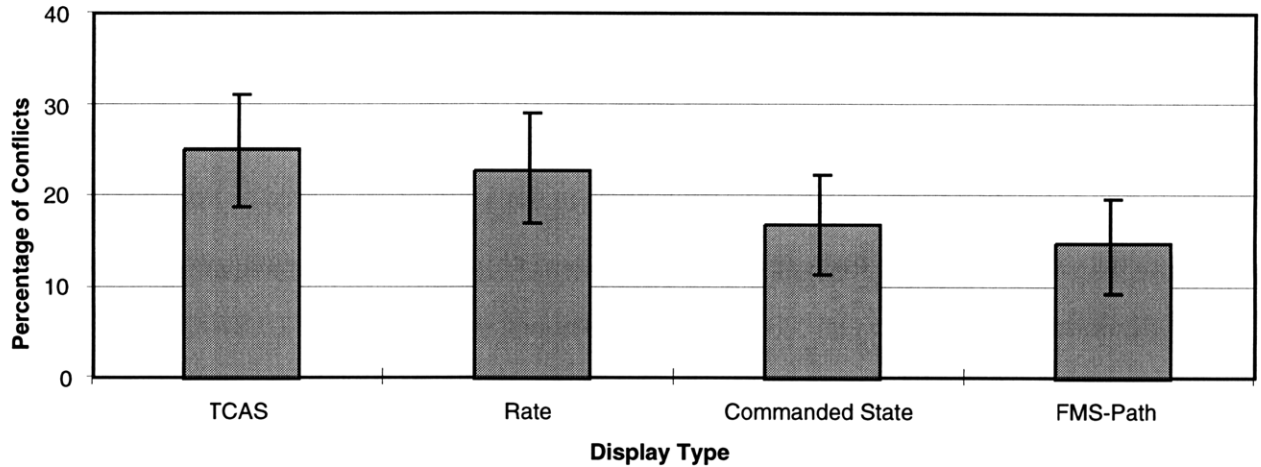
Figure 2.17: Total Separation Violations

Although the differences in separation violation percentage are insignificant between display types, there appears to be a trend toward decreasing separation violations with higher levels of intent information.

Display type affected the time in which subject pilots conducted an avoidance maneuver. Figure 2.18 shows the average time before separation violation that pilots initiated an avoidance maneuver. The zero time at the top of the graph is the time that a separation violation would have occurred if no maneuver was taken.
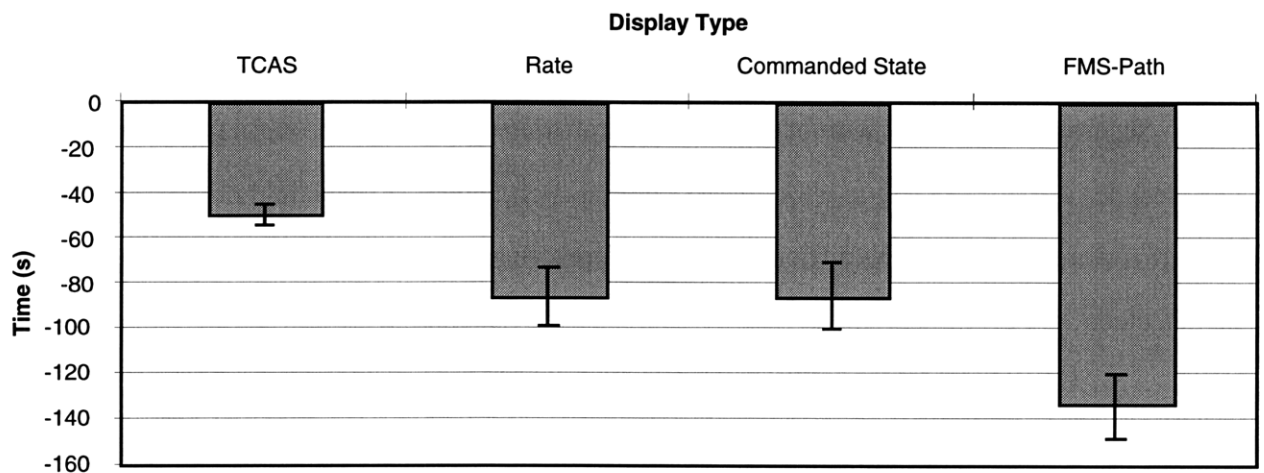
Figure 2.18: Average Time Before Separation Violation When Avoidance Maneuver Initiated

Three distinct groups of avoidance maneuver times can be observed. Pilots maneuver latest with the TCAS Display, followed by the Rate and Commanded State Displays and earliest with the

FMS-Path Display. Significant differences exist between the TCAS and the Rate or Commanded State Displays ($p < 0.01$) and between the Rate or Commanded State Displays and the FMS-Path Display ($p < 0.001$). Differences between the Rate and Commanded State Displays are insignificant.

Any combination of the three features added to the TCAS Display to produce the Rate Display (conflict bands, display of rate information, or profile view) could have contributed to the difference in maneuver times between the two displays. The small difference between the Rate and Commanded State Displays suggest that the addition of commanded heading and altitude to the Rate Display had little effect on when pilots maneuvered, but may have affected the type of maneuver.

Two key differences exist between the Commanded State and FMS-Path Displays. The LNAV/VNAV path information is added to the display and the conflict probe predicts conflicts based on both the intruder's FMS-Path and current state information. A conflict band is drawn if either of the two methods predict a conflict. Since future trajectory information is considered, the FMS-Path Display always produces a conflict band at the same time or earlier than the Rate or Commanded State Displays. The average time before separation violation that a conflict band appeared for the displays incorporating a conflict probe is shown in Figure 2.19.
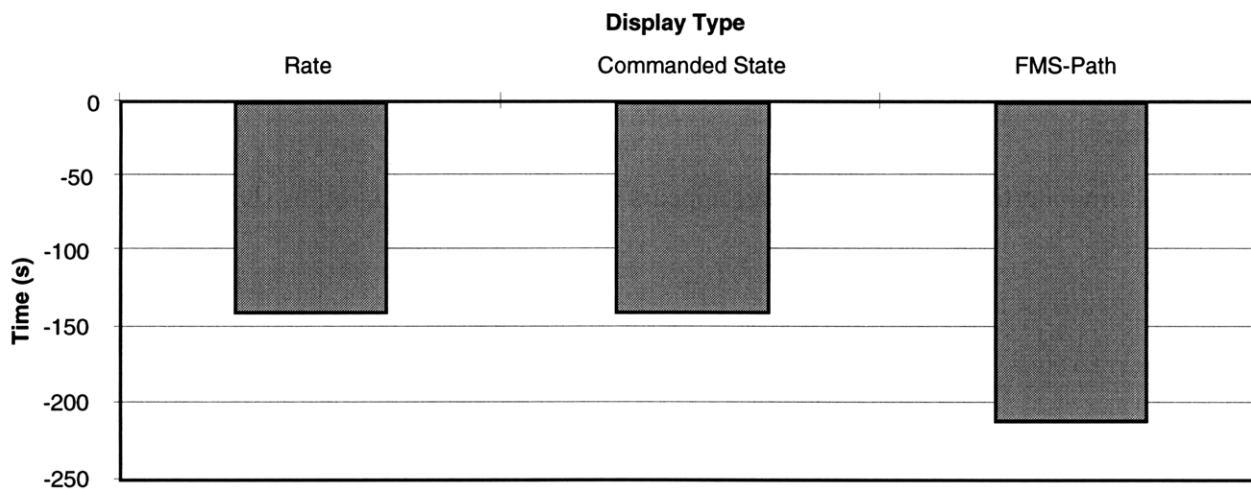
Figure 2.19: Average Time Before Separation Violation that a Conflict Band Appeared

On average, a conflict band based on FMS-Path information appeared 72 seconds earlier than one based only on current state information. One should note that these quantities are deterministic and depend only on the design of the scenarios for this experiment.

Even though pilots maneuvered earliest with the FMS-Path Display, they tended to wait longer after a conflict band appeared than they did with the Rate or Commanded State Displays. This result is shown in Figure 2.20. Differences between the Rate and Commanded State Displays are insignificant, but differences between the Commanded State and FMS-Path Displays are significant ($p < 0.01$).
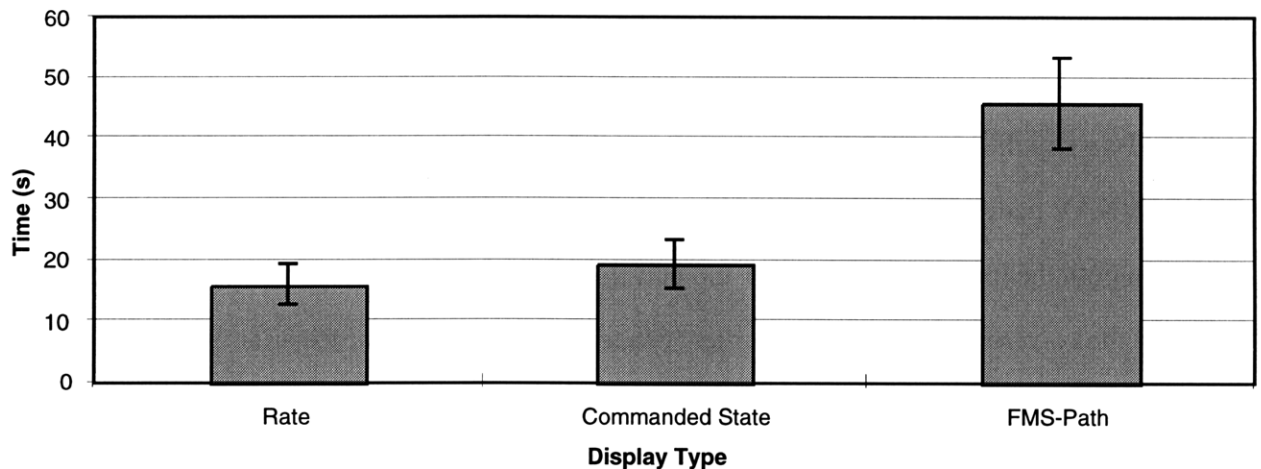
Figure 2.20: Time to Initiate Avoidance Maneuver After Conflict Band Appeared

This result suggests that pilots are either taking longer to process information on the FMS-Path Display or the FMS-Path conflict band appears too early for pilots to consider an avoidance maneuver.

Being alerted to conflicts earlier appears to be a significant asset, as shown in Figure 2.21.
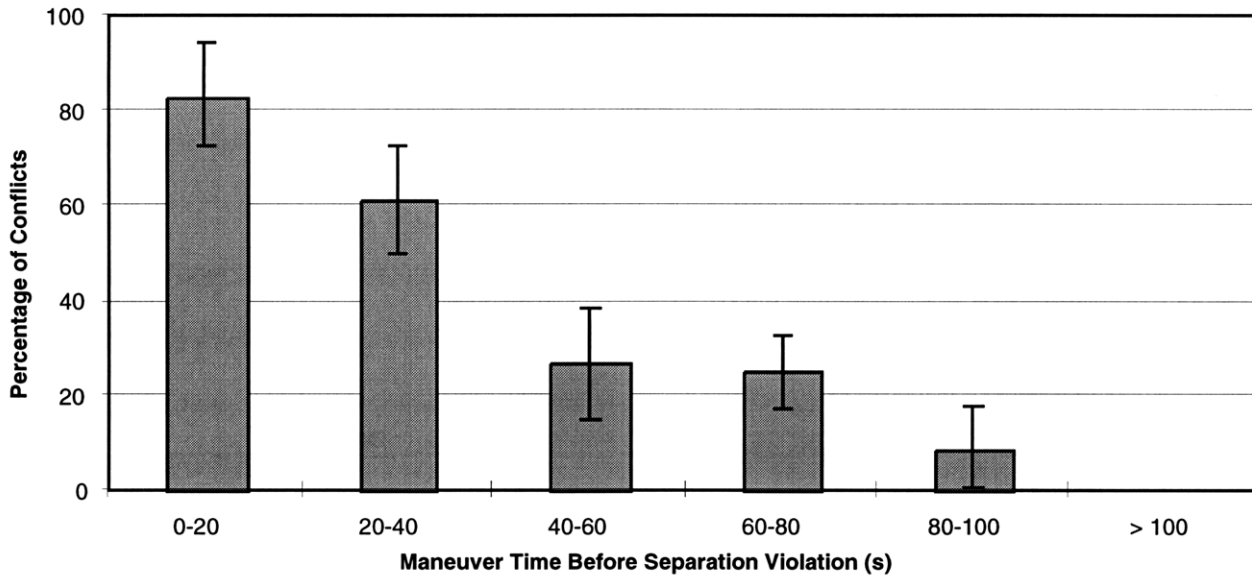
Figure 2.21: Percentage of Conflicts Resulting in Separation Violation vs. Maneuver Time

Figure 2.21 is a histogram of the percentage of conflicts resulting in separation violation when the subject pilot maneuvered at different time intervals before the conflict. The plot clearly shows a benefit to maneuvering earlier. When pilots waited until within 20 seconds of a conflict, they were unable to avoid a separation violation over 80% of the time. Performance improved monotonically as pilots maneuvered earlier. The latest avoidance maneuver to result in a separation violation occurred 85 seconds before the conflict.

2.4.3 Objective Results: Scenario Specific

A further comparison between the current state Rate and Commanded State Displays and the future state FMS-Path Display can be made by considering the results of the two scenarios producing the most separation violations. Figure 2.22 shows the separation violation percentage for each of the five scenarios averaged across all display types.
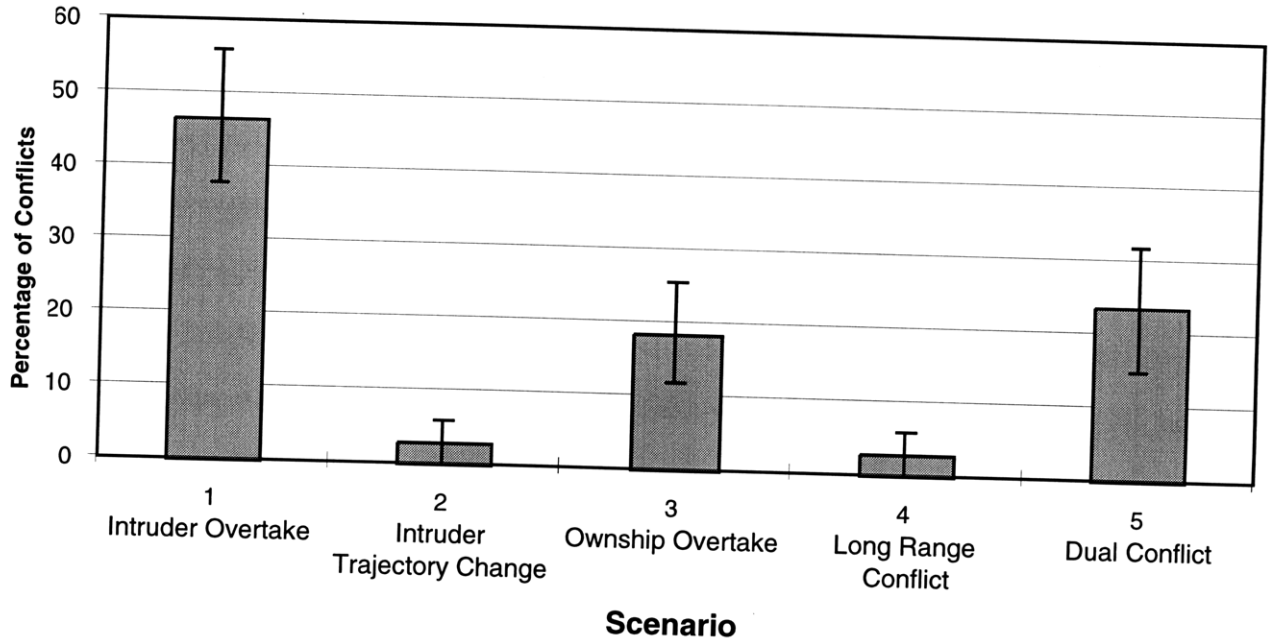
Figure 2.22: Separation Violation Percentage vs. Scenario

The highest percentage of separation violations (48%) occurred with Scenario 1, the Intruder Overtake. The next most difficult scenario was Scenario 5, the Dual Conflict, in which 23% of all conflicts and 38% of all scenarios resulted in a separation violation.

Figure 2.23 shows a plot of separation violation percentage vs. display type for Scenario 1, the Intruder Overtake and Scenario 5, the Dual Conflict.
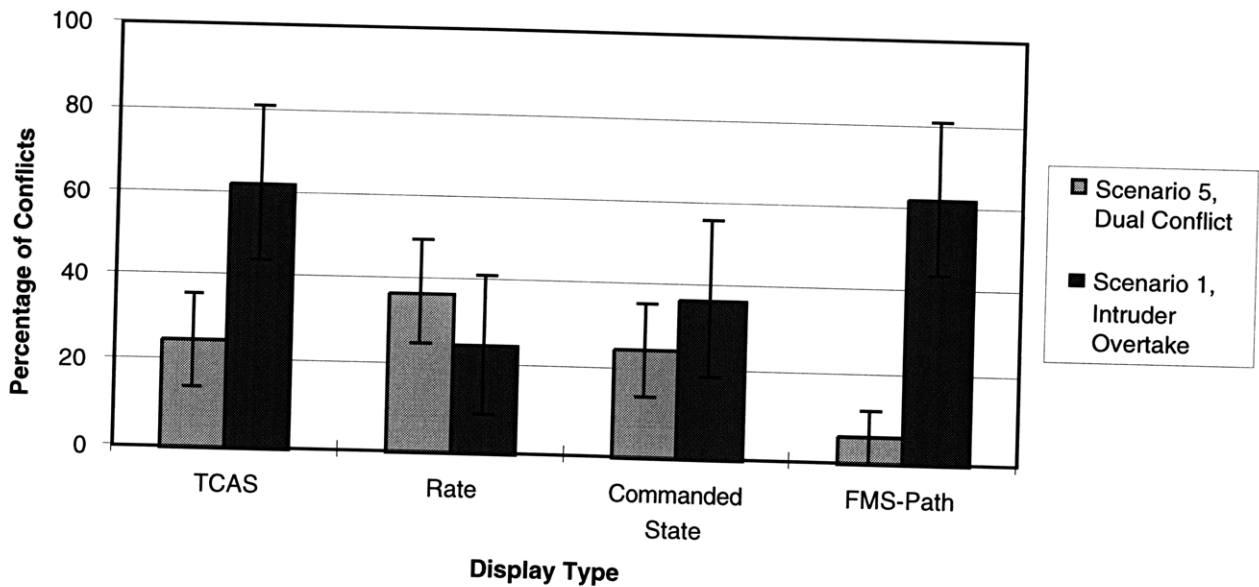
Figure 2.23: Separation Violation Percentage vs. Display Type

54

In addition, the time the conflict band appeared and the maneuver time is shown in Figure 2.24.
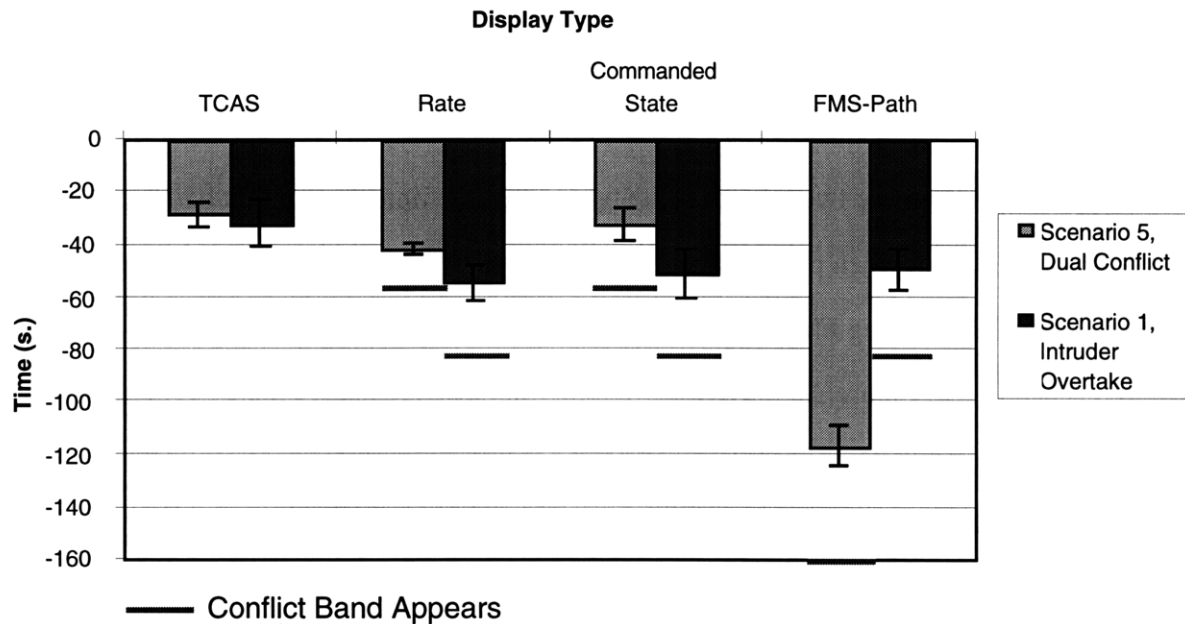
Display Type

Figure 2.24: Maneuver Time Before Separation Violation vs. Display Type

Pilots performed significantly better with the FMS-Path Display when compared to the Rate or Commanded State Displays on Scenario 5, the Dual Conflict ($p < 0.05$), but not on Scenario 1, the Intruder Overtake. Figure 2.24 highlights a major difference in these two scenarios.

On Scenario 5, the Dual Conflict, the FMS-Path conflict band appears at the beginning of the scenario, 160 sec. before separation violation. For the Rate and Commanded State Displays, the conflict band does not appear until 56 sec. before separation violation, when the first intruder starts to descend toward the subject pilot's aircraft. The conflict band on the FMS-Path Display gives a full 104 sec. of additional alert time. Pilots appeared to take advantage of this additional alert time by maneuvering an average of 78 sec. earlier with the FMS-Path than they did with the Rate or Commanded State Displays ($p < 0.01$).

When pilots don't maneuver earlier, the FMS-Path Display appears to offer little additional benefit to the other intent displays. On Scenario 1, the Intruder Overtake, the conflict band appears at the same time for all three displays and the pilots tended to maneuver at nearly the same time. On this scenario, the only difference between the FMS-Path and the Rate and Commanded State

Displays is the depiction of the FMS-Path instead of the current and next commanded state information. Showing multiple future states as opposed to only the next state on the display appears to have very little effect on when the pilot maneuvers or on whether a separation violation occurs.

By examining these two scenarios, it appears that the time the conflict band appears plays a more significant role in when pilots maneuver and in their ability to avoid conflicts than does the difference between showing FMS-Path and current/next commanded state information on the display. As shown in Figure 2.21, a display feature that leads to earlier maneuvers, up to several minutes before the conflict, appears to be an asset. However, with longer range alerts, the number of false alarm conflicts and unnecessary maneuvers would likely increase.

Another example of an earlier alert issued by the FMS-Path Display can be seen in Scenario 2, the Intruder Trajectory Change. In this scenario, the intruder programs a turn into the ownship one minute before reaching its next waypoint, causing a conflict band to appear on the FMS-Path Display. The conflict band appears on the Rate and Commanded State Displays when the intruder turns into the ownship, alerting the pilot two minutes before a separation violation occurs. The maneuver time vs. display type is shown in Figure 2.25.
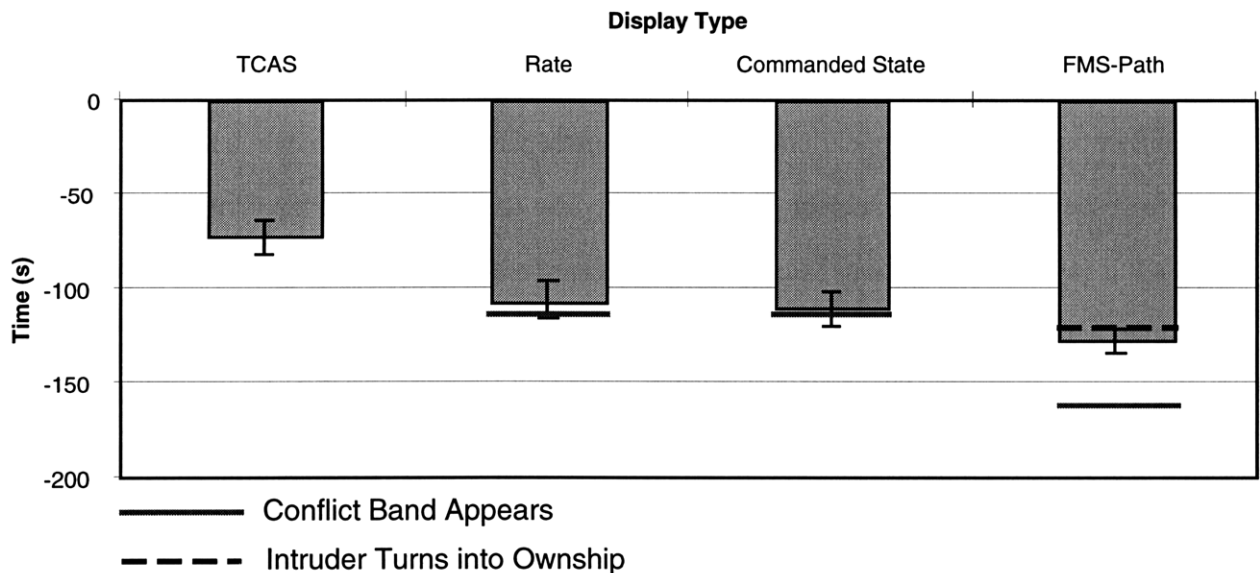
Figure 2.25: Scenario 2, Intruder Trajectory Change: Maneuver Time Before Separation Violation

On average, pilots maneuvered before the intruder reached the turn-in waypoint when flying with the FMS-Path Display. As opposed to Scenario 5, the Dual Conflict, where the FMS-Path Display led to significantly fewer separation violations, pilots did not appear to have a problem avoiding the conflict in this scenario. Only one out of a possible 32 conflicts resulted in a separation violation. The results of this scenario reaffirm that pilots tend to maneuver when shown a conflict band based on FMS-Path information. However, there appears to be little benefit to this earlier alert when the intruder commences a turn, climb, or descent toward the ownship several minutes before the conflict.

In addition to the long range conflict, Scenario 4 included an event where an intruder started a descent into the ownship but leveled off 1000 feet above the ownship altitude. A conflict band based on current state information was drawn for all three intent displays and didn't disappear until the intruder started to level-off. A profile view of the level-off event is shown in Figure 2.26.
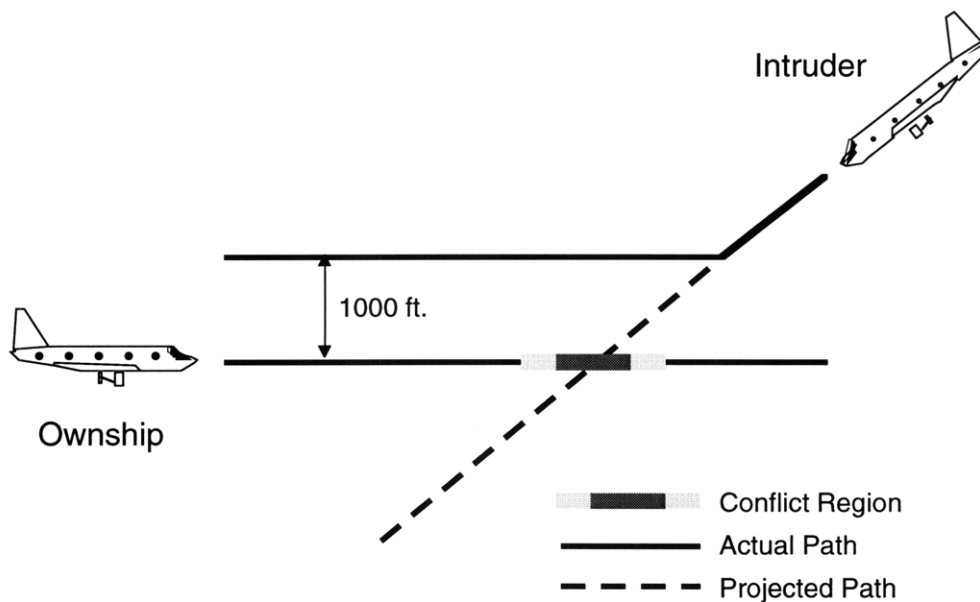
Figure 2.26: Profile View of Scenario 4, Intruder Level-Off

A level-off event was scripted to occur with each run of Scenario 4, the Long Range Conflict and Intruder Level-Off. However, many pilots maneuvered early in response to the long range conflict and never encountered the level-off event. On cases where the level-off event did occur, pilots

maneuvered 5 out of 6 times (83%) with the Commanded State Display and 4 out of 4 times with the FMS-Path Display. Pilots maneuvered as frequently for these displays showing the intruder's intentions to level-off as they did for the Rate and TCAS Displays. On this particular event, pilots did not seem to notice the level-off information or may have been unwilling to rely on it. Likewise, pilots may also have maneuvered in response to the conflict band shown on the display.

2.4.4   Subjective Results

The overall rankings for pilot display preference are provided in Figure 2.27.
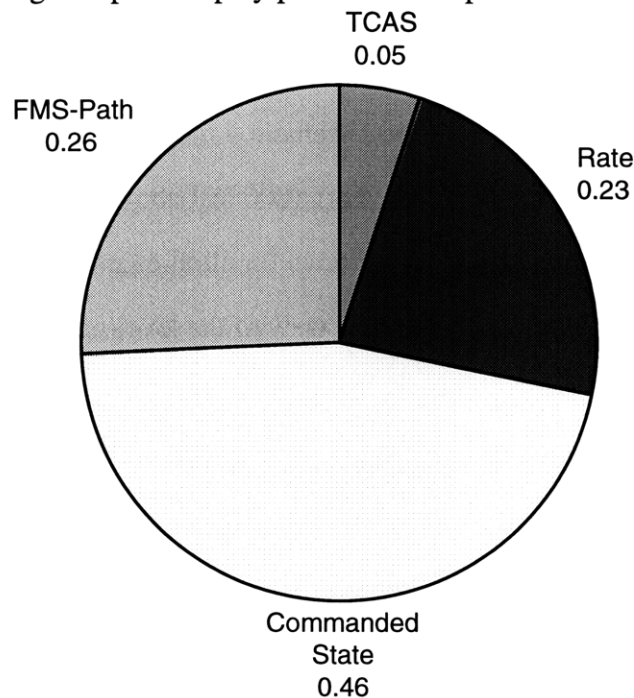
Figure 2.27: Pilot Display Preference

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.

In addition to rating the displays, pilots were asked to indicate which displays were too cluttered. Figure 2.28 shows these results.
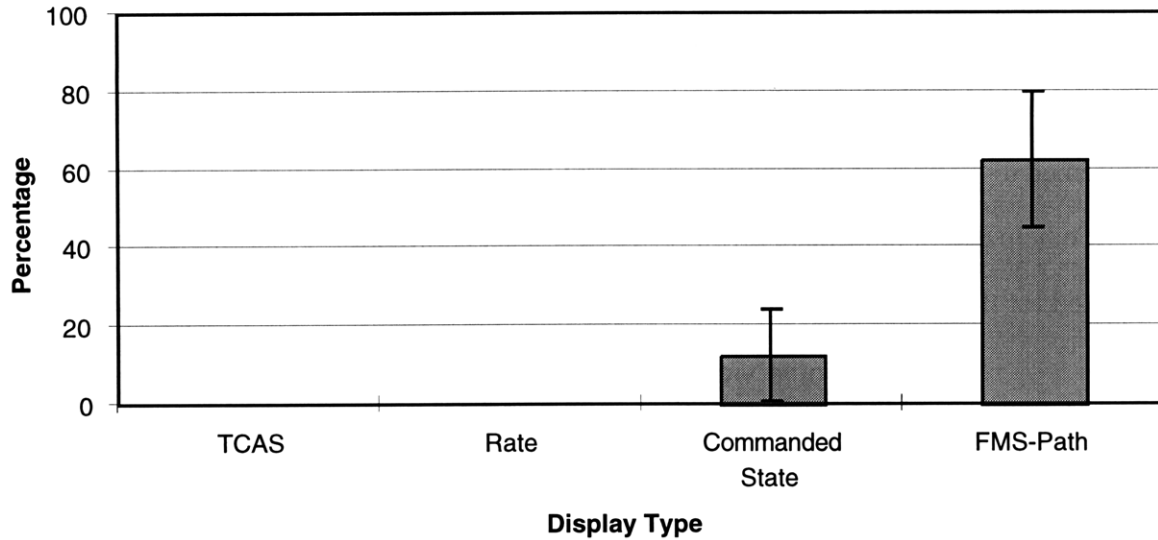
Figure 2.28: Percentage of Pilots Indicating Display Was Too Cluttered

More than half of the pilots found the FMS-Path Display to be too cluttered, a significantly higher percentage than any of the other displays ($p < 0.05$).

Another question asked pilots to rate each element of intent information, if available, for its value in enabling them to recognize and resolve traffic conflicts. The average scores are given in Figure 2.29.

SCALE
1: Very Detrimental
2: Somewhat Detrimental
3: Neutral
4: Somewhat Valuable
5: Very Valuable
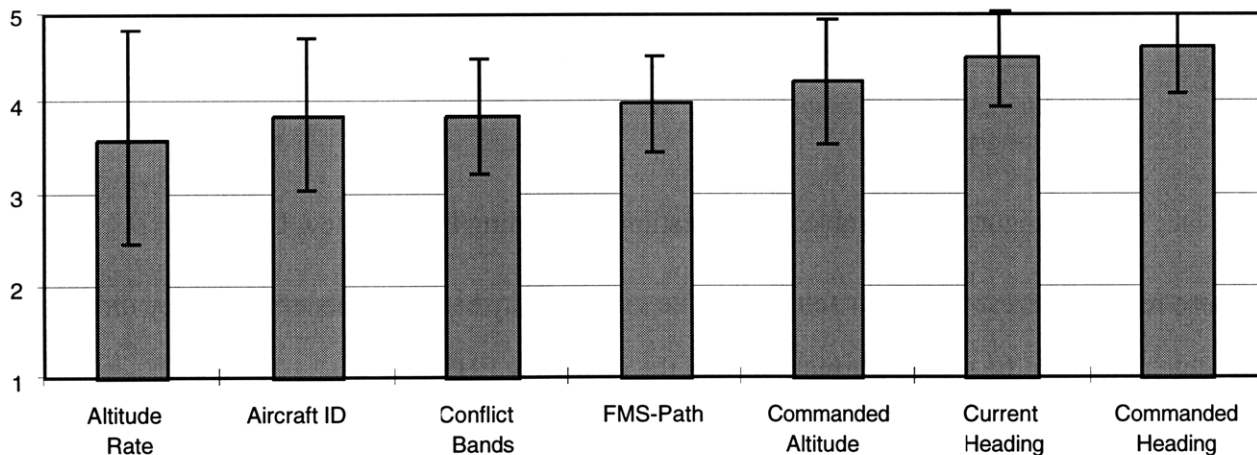
Figure 2.29: Value of Information Elements

The "Altitude Rate" refers to the altitude rate arrow on the profile view Rate Display and not to the standard TCAS altitude rate arrow on the plan view display. Although all information elements were deemed to have some value, current and commanded state information scored the highest.

To help determine whether the profile view display provided an additional benefit, pilots were asked for their level of agreement with the two questions shown in Figure 2.30.

"The profile view display made me more aware of the traffic situation in the vertical plane."

"I could get traffic information as easily from the EHSI as I could from the profile view display."

Figure 2.30: Subjective Questions Regarding Profile View Display

These results suggest that pilots felt the profile view display had some benefit, but they didn't have trouble obtaining the same information from the plan view EHSI.

2.5 Discussion

Both objective and subjective data suggest that there is a benefit to adding some level of intent information to the base TCAS Display. With the intent displays, pilots had fewer separation violations and tended to maneuver earlier to avoid conflicts. Separation violation data suggest that there is not an overall benefit to the FMS-Path Display over the other intent displays, although it did lead to better performance on Scenario 5, the Dual Conflict. Most pilots preferred the Commanded State Display, in addition to finding the FMS-Path Display to be too cluttered.

Seeing the lack of a clear benefit to providing FMS-Path information, one should take a closer look at the many practical issues involved with implementing such a display. As discussed previously, the FMS trajectory was simplified to a basic linear model, neglecting speed changes, mode transitions, and differences in FMS architecture between aircraft. Considering that numerous problems have been documented with pilots becoming confused over the state of 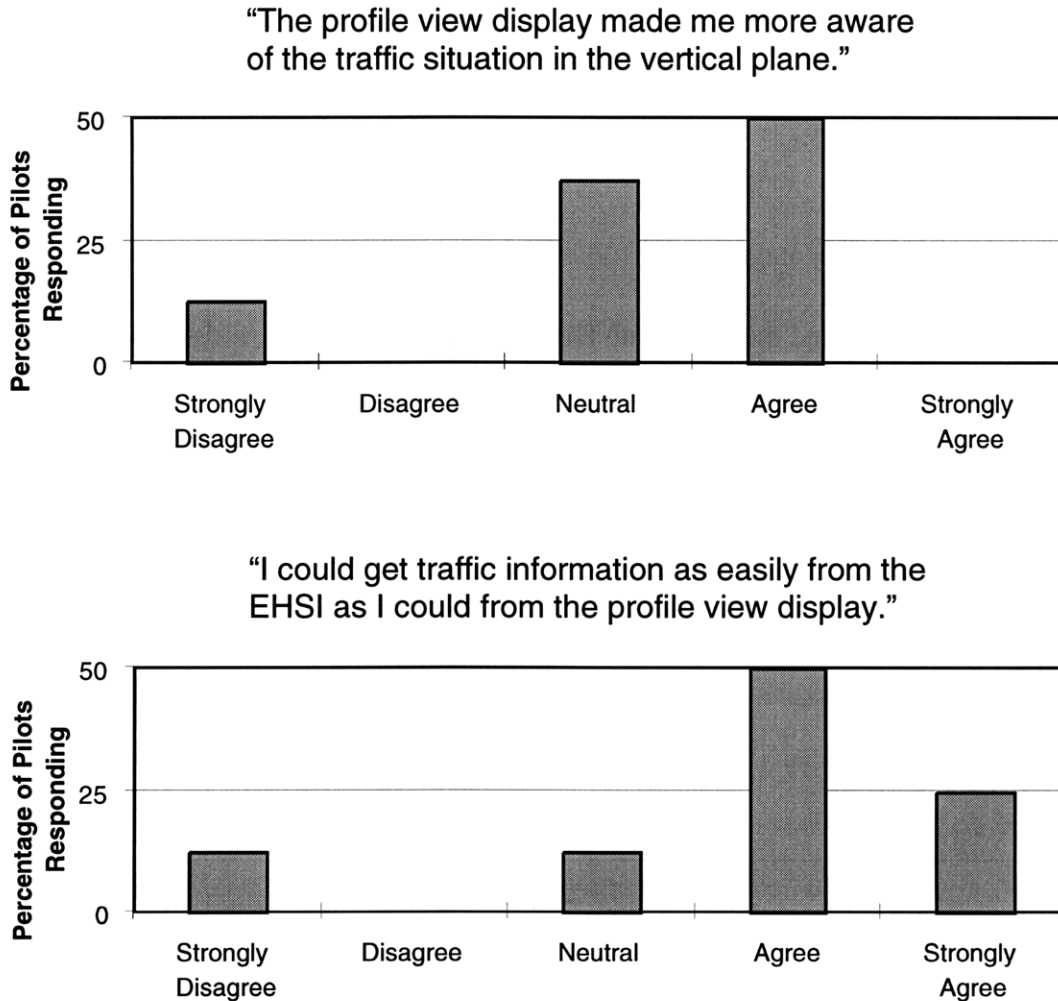their own aircraft (Vakil and Hansman, 1995), one could question whether pilots would be capable of monitoring and interpreting the states of other aircraft. In addition, all intruder aircraft flew in LNAV/VNAV mode during the experiment, so FMS-Path information was always available. A real FMS-Path Display would not be able to show LNAV and VNAV information for aircraft flying in manual or state modes or for those unequipped with an FMS. These "mixed mode" operations were not considered in this experiment.

A profound decrease in separation violations was observed when pilots maneuvered earlier. This result suggests that displays that encourage pilots to maneuver earlier, within several minutes of the conflict, are beneficial. No separation violations were observed in cases where pilots maneuvered at least two minutes before the conflict. Considering the likelihood of more alerts and unnecessary avoidance maneuvers as the alert time increases, a display that alerts pilots within several minutes of the conflict may be advantageous to one that issues even longer range alerts.

For the Rate, Commanded State, and FMS-Path Displays, results suggest that the time the conflict band appears has a greater affect on when pilots maneuver than does the level of intent information shown directly on the display. Across all scenarios, the Rate and Commanded State

Displays led to similar maneuver times. Also, pilots maneuvered at about the same time for the three enhanced displays on scenarios where the current state and FMS-Path based conflict bands appeared at the same time.

The results of the first experiment led to three key questions that warranted further study. First, which of the three additions to the TCAS Display: conflict bands, intent information shown on the display, or the profile view were most responsible for the reduction in separation violations and the earlier maneuver times? Secondly, would pilots perform as well with a display that alerts several minutes in advance of a conflict as with one that has a longer range alert? Finally, is there an added benefit to a plan/profile view combination over a plan view display alone?

Chapter 3

Experiment 2

The second experiment examined the individual and collective effect of displaying intent information directly to the pilot and incorporating it into a conflict probe. The Test Matrix is shown in Table 3.1. The matrix was evaluated on four new traffic scenarios and was counterbalanced by varying the order of the six display options.

Table 3.1: Experiment 2 Test Matrix

Applied Intent Information

Displayed Intent Information		No Conflict Band	Conflict Band with 2 Minute Look-Ahead	Conflict Band with Long Range Look-Ahead
	TCAS	X	X	X
	Commanded State	X	X	X

The TCAS and Commanded State Levels were tested as two different ways to display intent information to the pilot. The Commanded State Display was chosen to represent the three enhanced displays from Experiment 1 since it led to similar performance, was preferred by the pilots, and would be easier to implement than the FMS-Path Display.

Intent information can also be incorporated into the display through the use of a conflict probe. Cases were run with and without a conflict probe. To compare performance with short and long range alerts, conflict probes with two minute and long range look-ahead times were tested. With the two minute look-ahead, a conflict band only appeared within two minutes 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 projected.

Finally, to evaluate pilot performance with and without a profile view, the Commanded State Display was modified to include only a plan view. In order to provide a direct comparison, the same Intruder Overtake Scenario used in Experiment 1 was included in the scenario set.

3.1   Display Design

Four different displays were tested, corresponding to the options of TCAS and Commanded State, with and without conflict bands. All displays provided only a plan view.

3.1.1   TCAS Display

The TCAS Display with Conflict Bands is shown in Figure 3.1. Conflict prediction is based on current state information and the same separation criteria is used as in Experiment 1. The aircraft ID was always printed in white for displays without conflict bands.
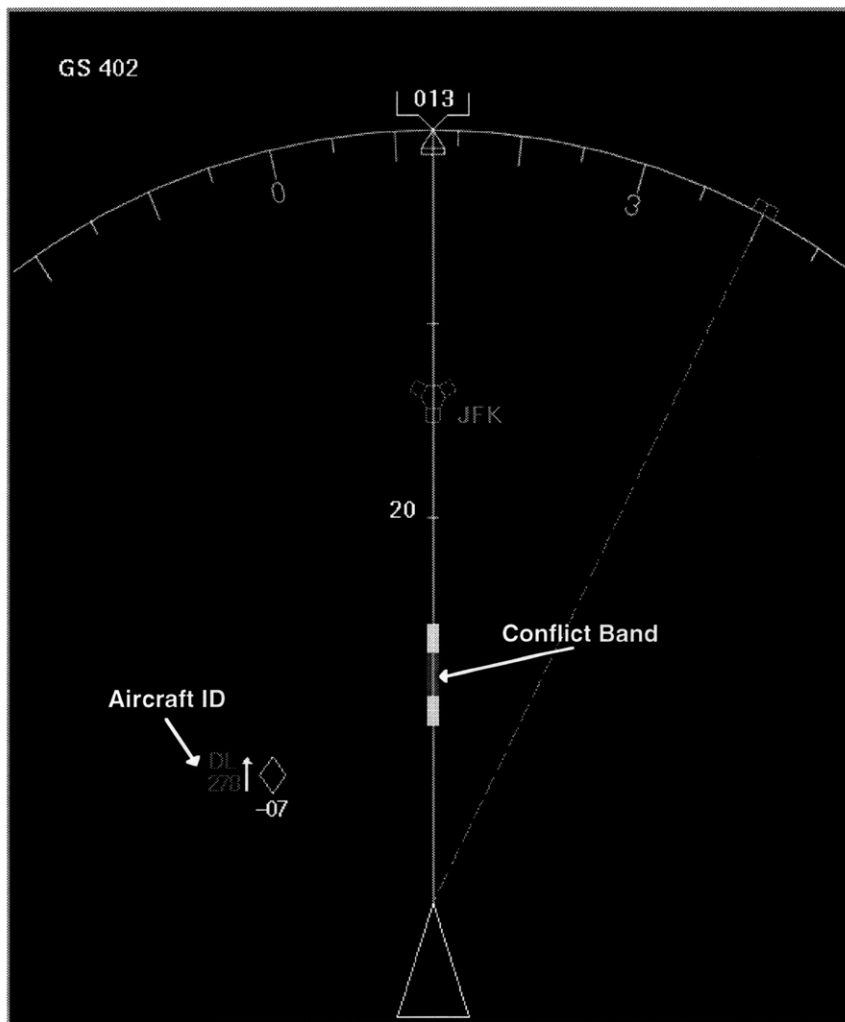
Figure 3.1: TCAS Display with Conflict Bands

3.1.2   Commanded State Display

A minor change was made to the Commanded State Display from Experiment 1. Since the profile view was not used, the commanded altitude was shown on the plan view display in magenta. The altitude shown is the relative altitude between the intruder's commanded altitude and the ownship's current altitude. A sample Commanded State Display with Conflict Bands is provided in Figure 3.2.
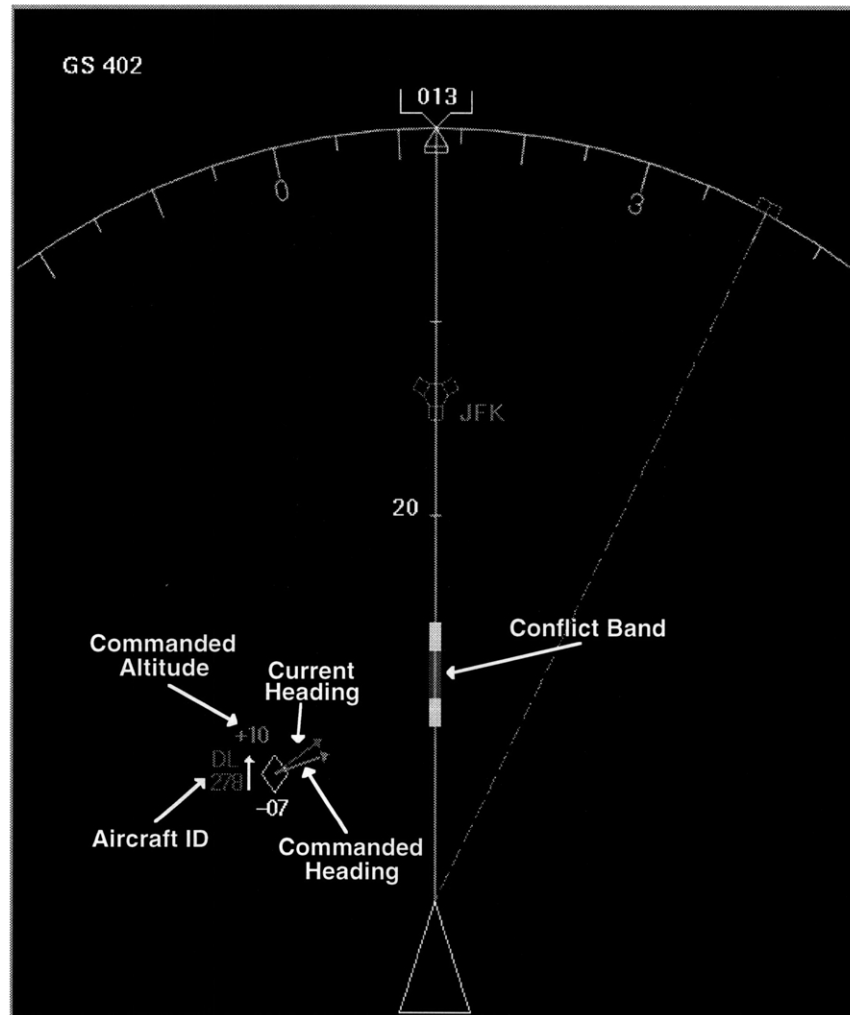
Figure 3.2: Commanded State Display with Conflict Bands

Unlike the first experiment, commanded state information was shown for all aircraft regardless of conflict status. Pilots were not able to deselect the information.

For the second experiment, pilots were given the option of showing the intruder's current and commanded altitude with respect to mean sea level or relative to the ownship, as depicted on the displays above. Six pilots used the relative altitude and two used the absolute altitude.

3.2 Scenario Design

Four scenarios were designed to highlight features of the displayed intent information and the conflict probe.

3.2.1 Scenario 1: Short Range Conflict

The Short Range Conflict Scenario is shown in Figure 3.3.
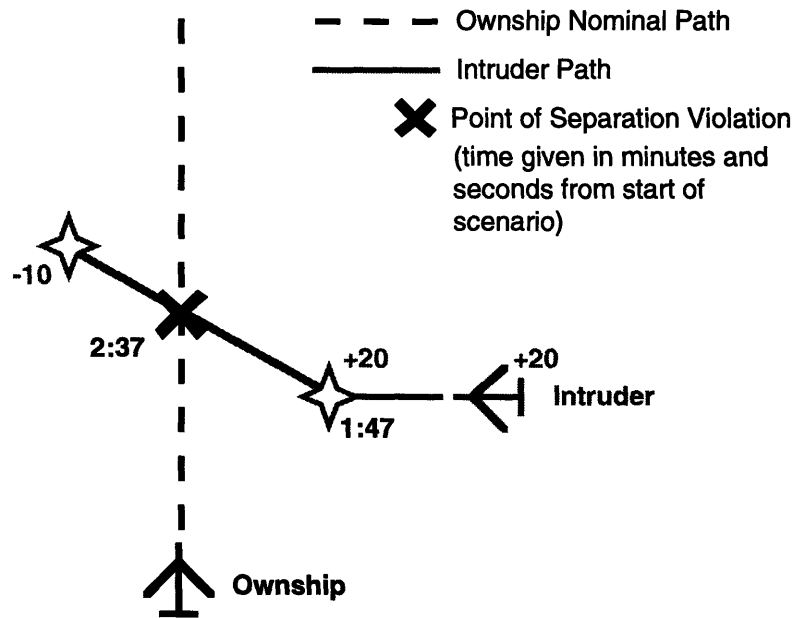
Figure 3.3: Short Range Conflict Scenario

The intruder turns and descends into the ownship fifty seconds before a separation violation. In this scenario, both the two minute and long range conflict bands appear when the intruder turns in. For this reason, it was expected that separation violations and maneuver times would be similar for both conflict band cases of the same display. The scenario was also designed to see how pilots would perform with the various display options under a close-in tactical conflict.

69

3.2.2 Scenario 2: Intruder Maneuvers During Conflict

This dynamic conflict scenario was designed to determine whether pilots could use intent information to detect an intruder that maneuvers toward them while they are maneuvering. Unlike the scenarios for Experiment 1 and the other scenarios for Experiment 2, the intruder's trajectory depends on the actions of the ownship. A drawing is given in Figure 3.4.
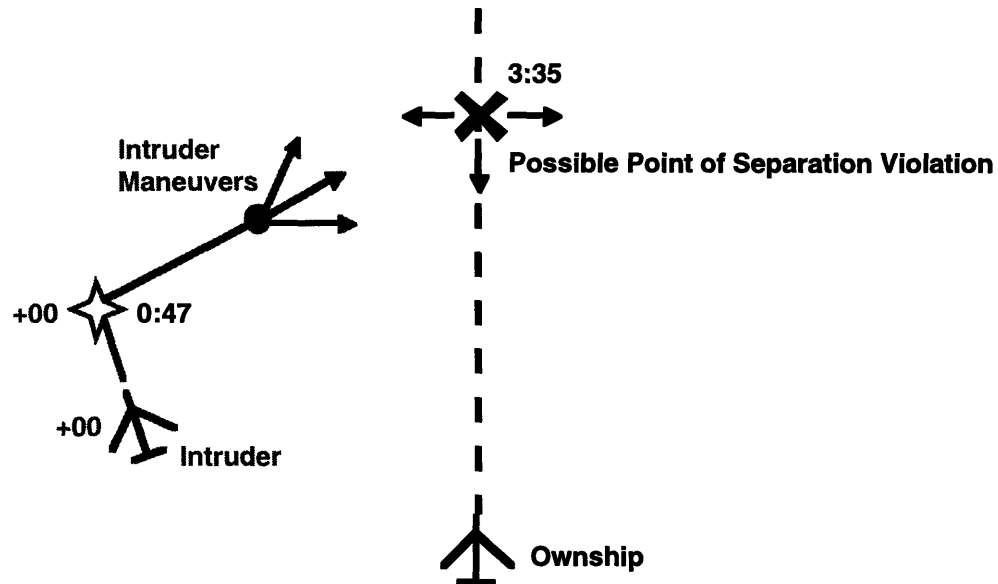
Figure 3.4: Intruder Maneuvers During Conflict Scenario

Forty-seven seconds from the start of the scenario (0:47), the intruder turns in to pass over the ownship's flight path co-altitude at 4:03, causing a separation violation at 3:35. Cues for the intruder to maneuver a second time are an ownship deviation of 15 degrees or 300 ft. from its original flight path. If the ownship triggers the turning cue first, the intruder turns into the ownship to recreate the conflict at 3:35. If the subject triggers the climb/descent cue first, the intruder climbs or descends to an altitude 1000 ft. above or below the subject's altitude at the time the cue is triggered. In each case, the traffic situation is made worse by the secondary maneuver of the intruder.

3.2.3 Scenario 3: Long Range Conflict

The Long Range Conflict Scenario, shown in Figure 3.5 is similar to the one used in Experiment 1.
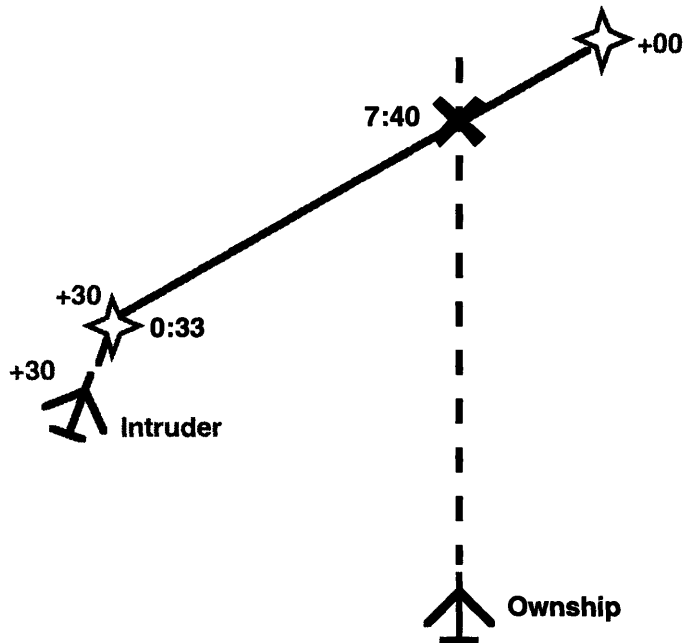
Figure 3.5: Long Range Conflict Scenario

Little data was obtained for the long range conflict in Experiment 1 due to the presence of the intruder level-off event. It was hoped that the long range conflict would show whether pilots' response time depended on the look-ahead time of the conflict band. Differences in maneuver times for all options of displayed and applied intent information were examined.

3.2.4 Scenario 4: Intruder Overtake and Multiple Conflict

The intruder overtake airplane is the same as the one used in the Intruder Overtake Scenario of Experiment 1. Separation violation with this aircraft happens at 1:22 if no avoidance maneuver is taken. In addition, a multiple conflict with three other aircraft is designed at 4:00. This scenario is drawn in Figure 3.6.
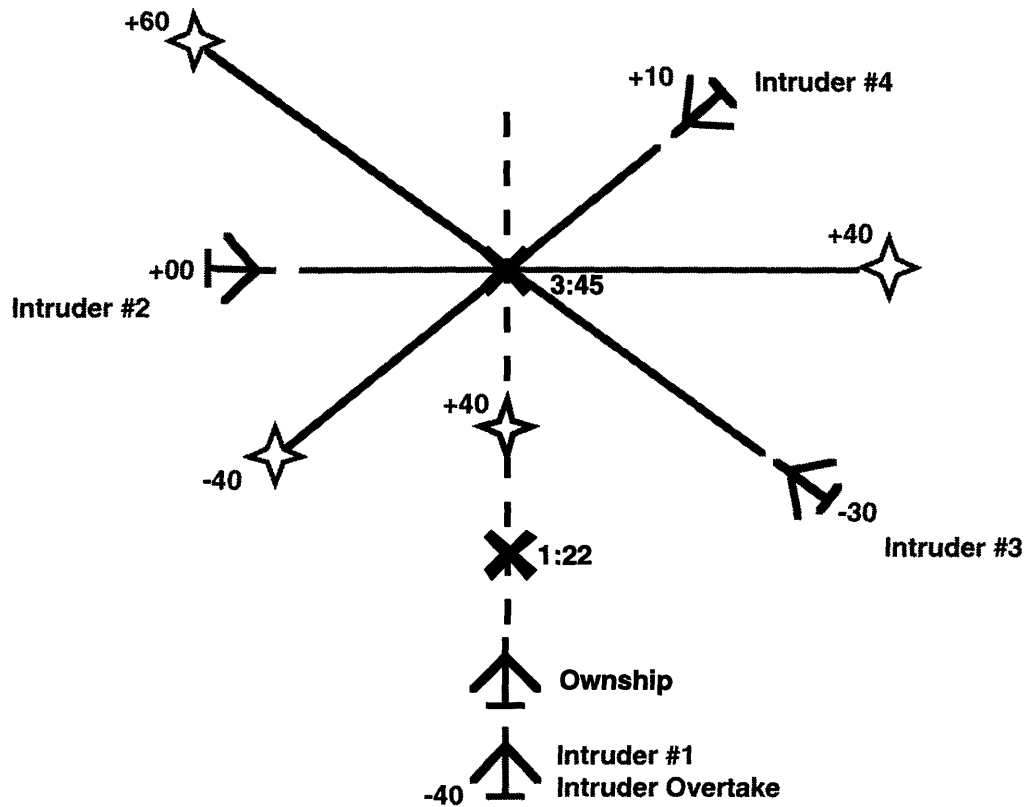
Figure 3.6: Intruder Overtake and Multiple Conflict Scenario

Conflict bands for the multiple conflict appear at the start of the scenario for the long range conflict band, but not for the two minute band. It was thought that pilots might become distracted by trying to interpret all of the conflicts, causing them to delay maneuvering for the nearest conflict. Separation violation differences between the two minute and long range conflict band were examined for each display. Results were also compared between this scenario and the Intruder Overtake Scenario from Experiment 1 to determine whether the profile view had a significant effect.

3.3 Method

3.3.1 Apparatus

The MIT Part Task Flight Simulator was again used as the experimental apparatus. Since pilots were unable to select or deselect intent information, the mouse was not used.

3.3.2 Procedure

The general procedure for each experimental run was identical to Experiment 1. As before, pilots were to fly direct to the VOR shown on the EHSI at 18,000 ft. unless necessary to avoid other traffic. After a conflict was resolved, pilots would turn back to the VOR and return to 18,000 ft. As in Experiment 1, the primary goal of each scenario was to maintain the required separation of 2 nm. laterally or 500 ft. vertically from all other traffic.

3.3.3 Training

A pre-experiment briefing similar to the first experiment was given to the pilots, a sample of which is provided in Appendix D. As with Experiment 1, aspects of the simulator, displays, and flight environment were reviewed. Practice scenarios were given before the experiment with the base TCAS Display and before conducting test runs using a display with new information.

3.3.4 Performance Metrics

As in the first experiment, the primary performance metrics were the percentage of conflicts resulting in a separation violation and the maneuver time. A similar subjective questionnaire was used at the end of the experiment. A sample is provided in Appendix E. Subjects were asked to give their preferred combination of intent information and conflict bands and to rate the value of the available information elements. Other questions asked for their collision avoidance strategies with and without intent information and conflict bands and for their opinion on the best time and range to issue an alert.

73

3.3.5 Data Analysis

Within subjects paired t-tests were again used to test for significance between means of separation violation percentage and maneuver time. All error bars shown on plots represent one standard error. A two factor within subjects ANOVA was also performed to test whether changing the displayed intent information or the look-ahead time on the conflict bands had an overall effect on the percentage of separation violations or the maneuver time. The AHP was used to produce overall rankings for pilot preference of display type and conflict band option.

3.4   Results

3.4.1   Subjects

Eight commercial airline pilots served as volunteer test subjects for the second experiment. 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 hours with a mean of 16,225 hours. Their ages ranged from 35 to 60 with a mean of 49. Six of the eight were captains and four had military flying experience.

3.4.2   Objective Results: Overall

The most direct result of pilot performance, the separation violation percentage, is plotted vs. display option in Figure 3.7. Each of the six display options of displayed and applied intent information had four possible conflicts per pilot. Only the intruder overtake conflict was considered for Scenario 4, the Intruder Overtake and Multiple Conflict. There were eight pilots, leading to a total of 32 conflicts per display option. As in Experiment 1, conflict scenarios were designed to be difficult.
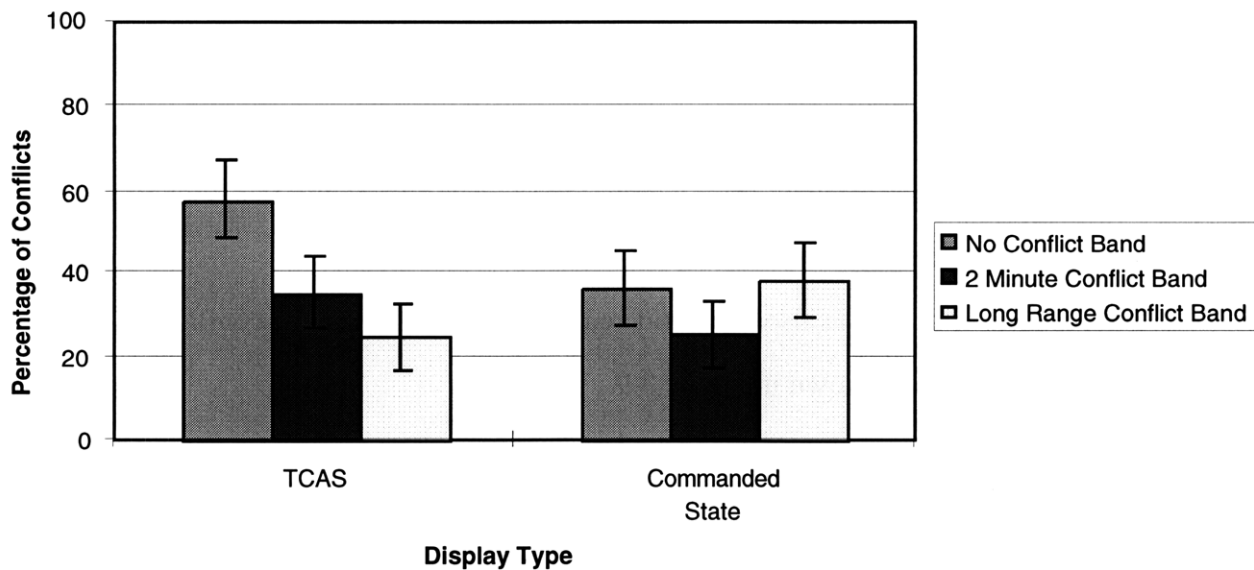

Figure 3.7: Total Separation Violations vs. Display Option

The results show that the addition of either conflict bands or intent information to the base TCAS Display resulted in fewer separation violations. Each enhanced option led to significantly better performance than the TCAS Display alone ($p < 0.05$). The differences between the two minute and long range conflict bands for each display type were insignificant ($p > 0.05$). A two factor ANOVA considering the effect of displayed and applied intent information showed that neither had a significant overall effect on the number of separation violations.

The time the subject pilots conducted an avoidance maneuver can be seen in Figure 3.8.

Display Type

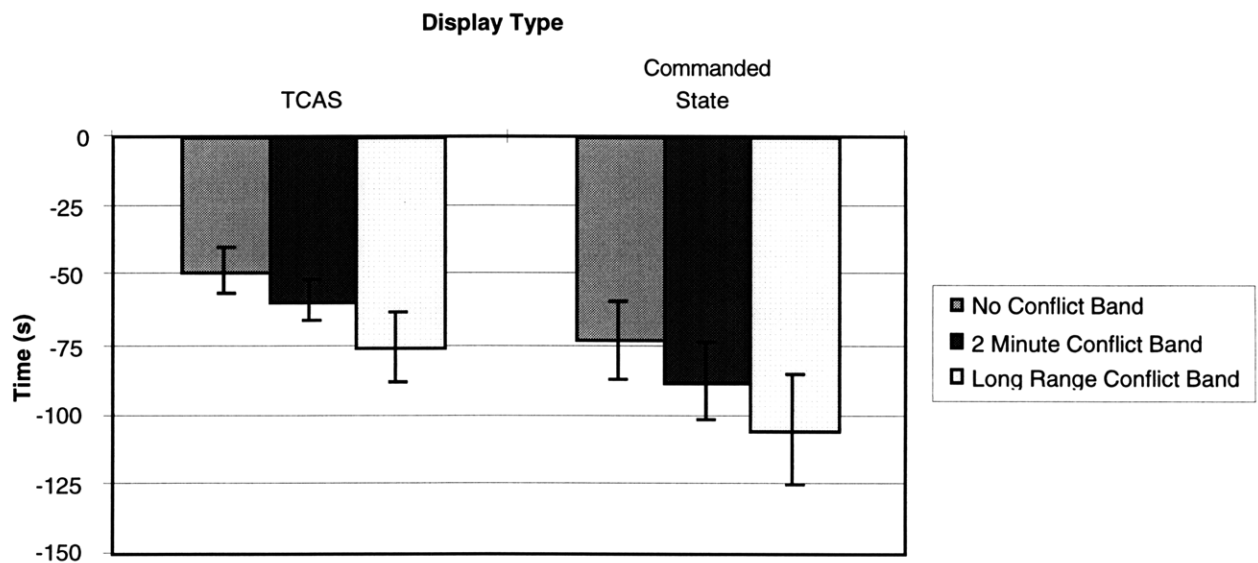Figure 3.8: Average Maneuver Time Before Separation Violation

Figure 3.8 shows that displaying either intent information or conflict bands cause pilots to make earlier avoidance maneuvers. A two factor within subjects ANOVA shows that both effects have overall significance ($p < 0.05$).

Pilot maneuver times can also be considered in reference to when the conflict band appeared. These results are shown in Figure 3.9.
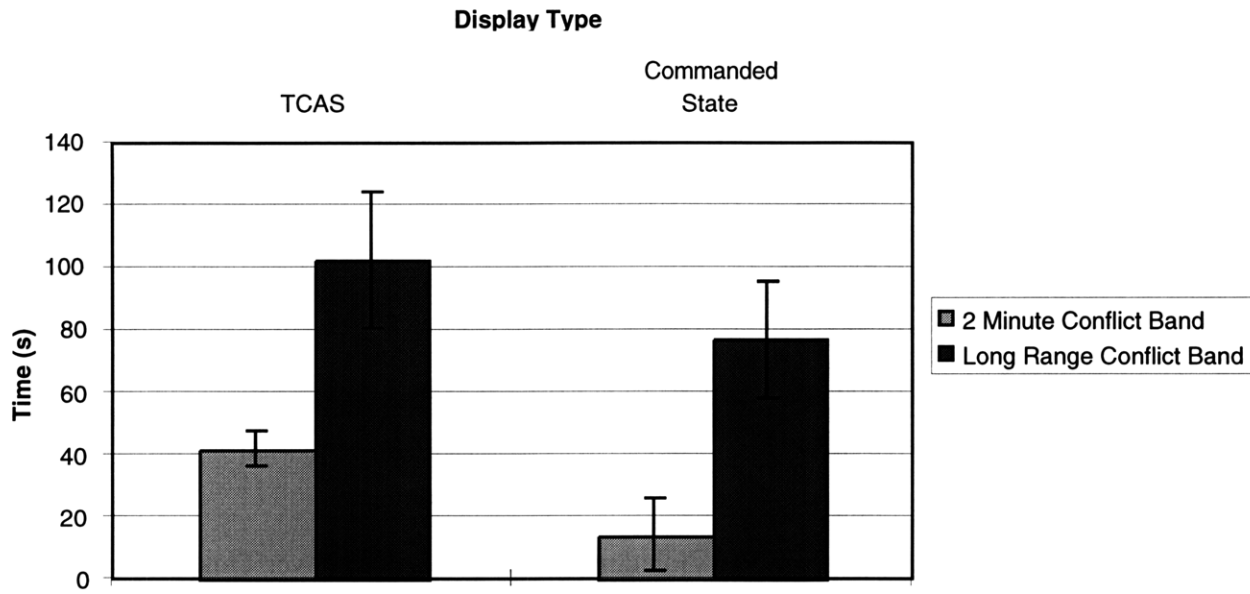
Figure 3.9: Average Time to Conduct Avoidance Maneuver After Conflict Band Appeared

Two significant results can be obtained from Figure 3.9. With the two minute conflict band, pilots maneuvered 42 sec. after the band appeared when using the TCAS Display and only 14 sec. after with the Commanded State Display. This difference is significant ($p < 0.01$). This result suggests that when given current and commanded state information, pilots are more willing to conduct an avoidance maneuver promptly when a conflict band appears. The intent information shown on the display seems to reinforce the issuance of the alert, thus reassuring pilots that an avoidance maneuver is appropriate.

With the long range conflict band, pilots waited over a minute to maneuver after the alert was issued. This significantly longer delay time with the long range band when compared to the two minute band for each display type ($p < 0.01$) implies that the pilots consciously ignored the longer alerts, possibly feeling that they were issued too early.

The relationship between the separation violation percentage and the maneuver time is shown in Figure 3.10.
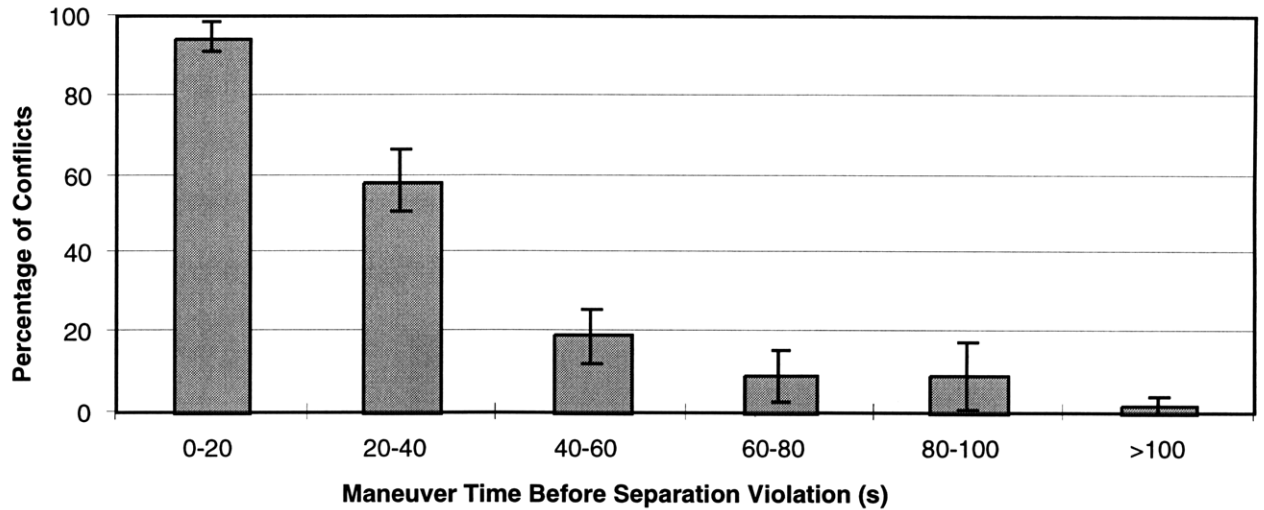
Figure 3.10: Separation Violation Percentage vs. Maneuver Time

As in Experiment 1, results indicate that pilots had fewer separation violations when they maneuvered earlier, with the most significant improvement occurring for maneuvers within two minutes of the conflict.

3.4.3   Objective Results: Scenario Specific

A complete set of separation violation and maneuver time plots for each scenario is provided in Appendix F. To isolate the benefits of conflict bands and intent information shown directly on the display, it is helpful to consider plots of separation violation percentage and maneuver time averaged across display type and conflict band option.

Figure 3.11 plots separation violations vs. scenario for the two display types, TCAS and Commanded State.
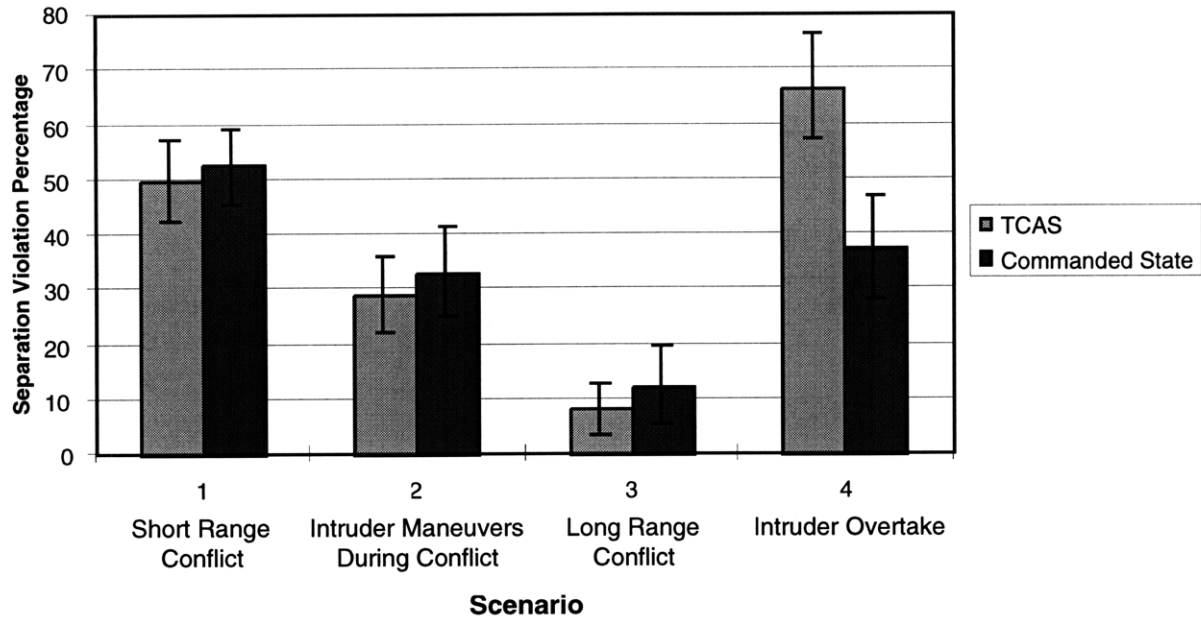
Figure 3.11: Separation Violation Percentage vs. Scenario and Display Type

Separation violations are averaged across all conflict band options. It is interesting to note that performance is very similar between the TCAS and Commanded State Displays except for Scenario 4, the Intruder Overtake, where pilots performed significantly better with the Commanded State Display ($p < 0.05$). One possible explanation is that pilots maneuvered earlier with the Commanded State Display for all conflict band options, as shown in Figure 3.12.
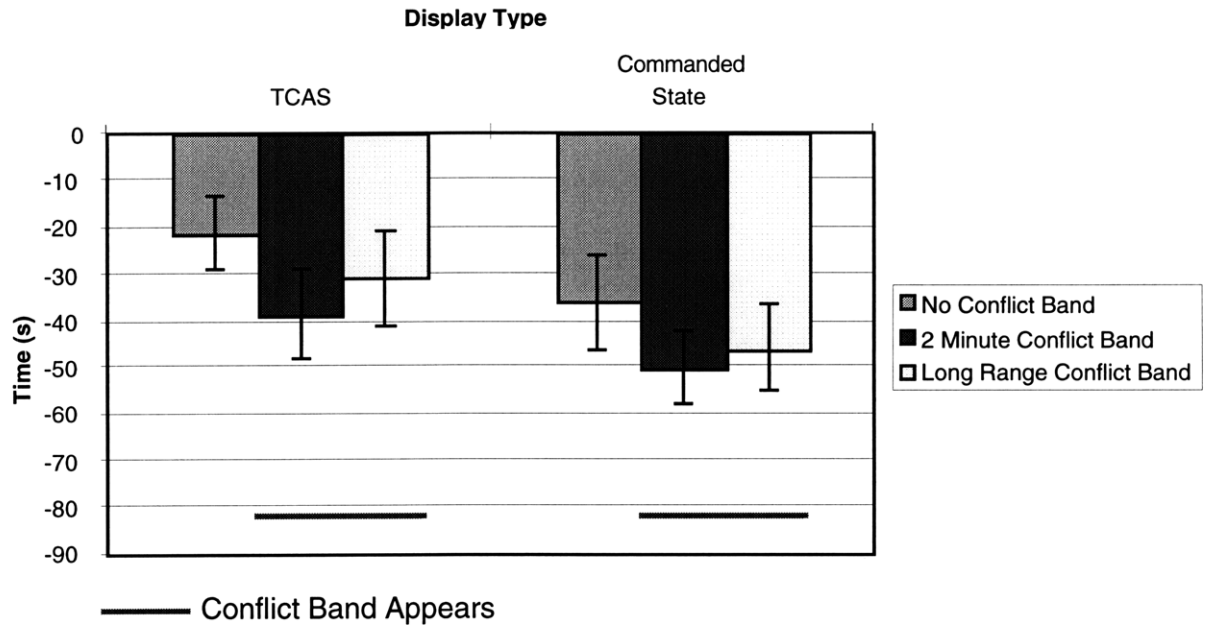
Figure 3.12: Scenario 4, Intruder Overtake: Maneuver Time Before Separation Violation

In this scenario, maneuver times averaged across all conflict band options are significantly earlier for the Commanded State Display ($p < 0.05$). The intruder overtake was a strictly vertical conflict, which suggests that the commanded altitude may have been a dominant factor in the earlier maneuvers.

In order to consider the performance effect of the conflict band, separation violations can be plotted for each scenario with and without the conflict band. These results are shown in Figure 3.13. The "with conflict band" data is the combined separation violation percentage for the 2 minute and long range look-ahead conflict bands.
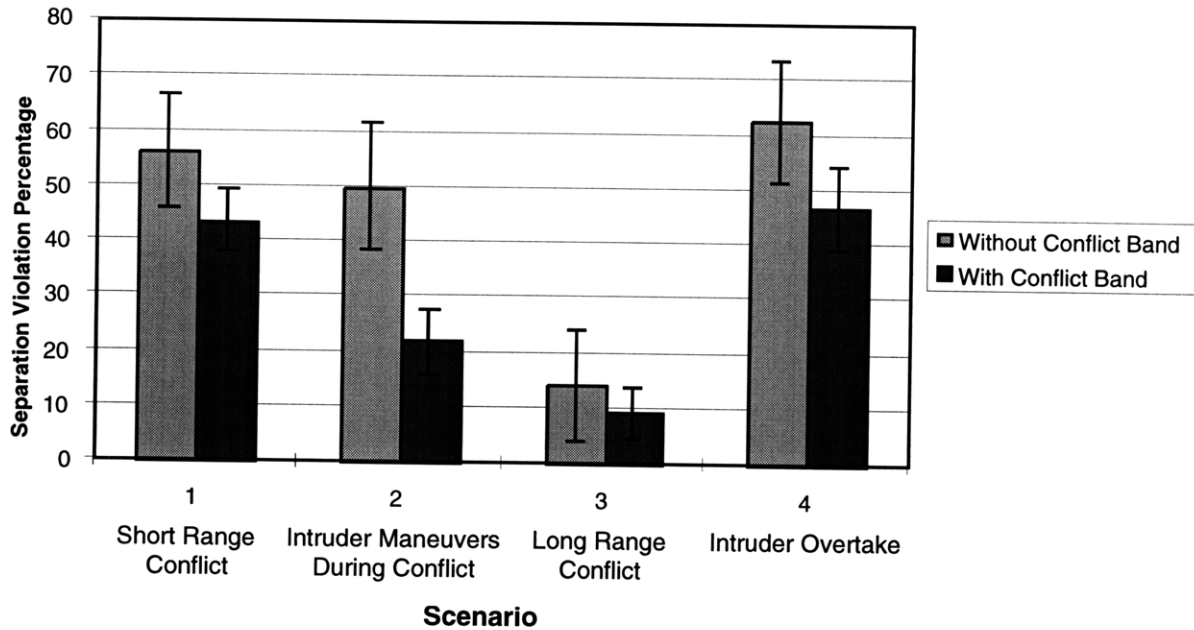
Figure 3.13: Separation Violation Percentage vs. Scenario and Conflict Band Option

The presence of the conflict band appears to reduce the number of separation violations for all scenarios, however, the result is only significant for Scenario 2, Intruder Maneuvers During Conflict ($p < 0.05$). This scenario involved the intruder maneuvering toward the subject at very close range. It is possible that the conflict band provided an immediate notification that the situation had deteriorated and could be interpreted more quickly than intent information shown on the display. The addition of displayed intent information without conflict bands did not appear to be helpful in this scenario, as seen from Figure 3.11.

One objective of the second experiment was to compare results between displays that showed both plan and profile views and those that had the plan view alone. The Intruder Overtake Scenario from Experiments 1 and 2 is used to make this comparison. Figure 3.14 shows the separation violation percentage for this scenario with the Commanded State Display. Each bar represents the percentage of eight conflicts that resulted in a separation violation.

Commanded State Display
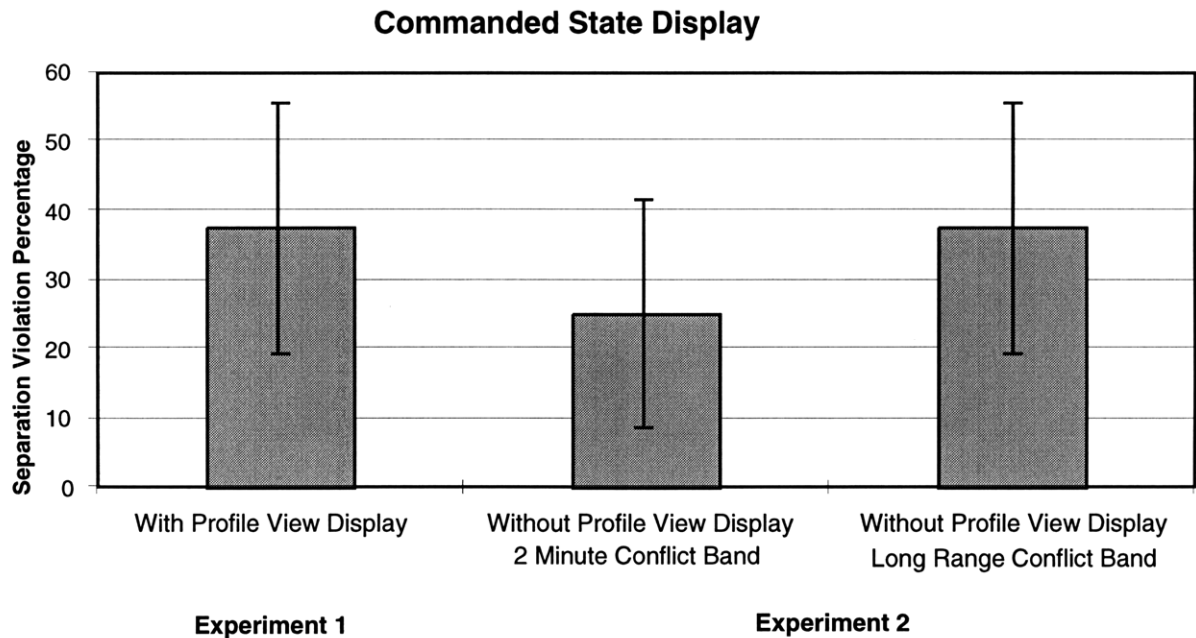
Figure 3.14: Separation Violation Percentage for Intruder Overtake Scenario
with and without Profile View Display

Performance is very similar regardless of whether the profile view display is used. In Experiment 2, a long range multiple conflict was added, making the Intruder Overtake Scenario more difficult than Experiment 1. Even so, pilots performed as well in both the two minute and long range conflict band cases.

Performance on Scenario 3, the Long Range Conflict is offered in contrast to the tactical scenarios discussed previously. Separation violation percentage varied little between display option, as shown in Figure 3.15.
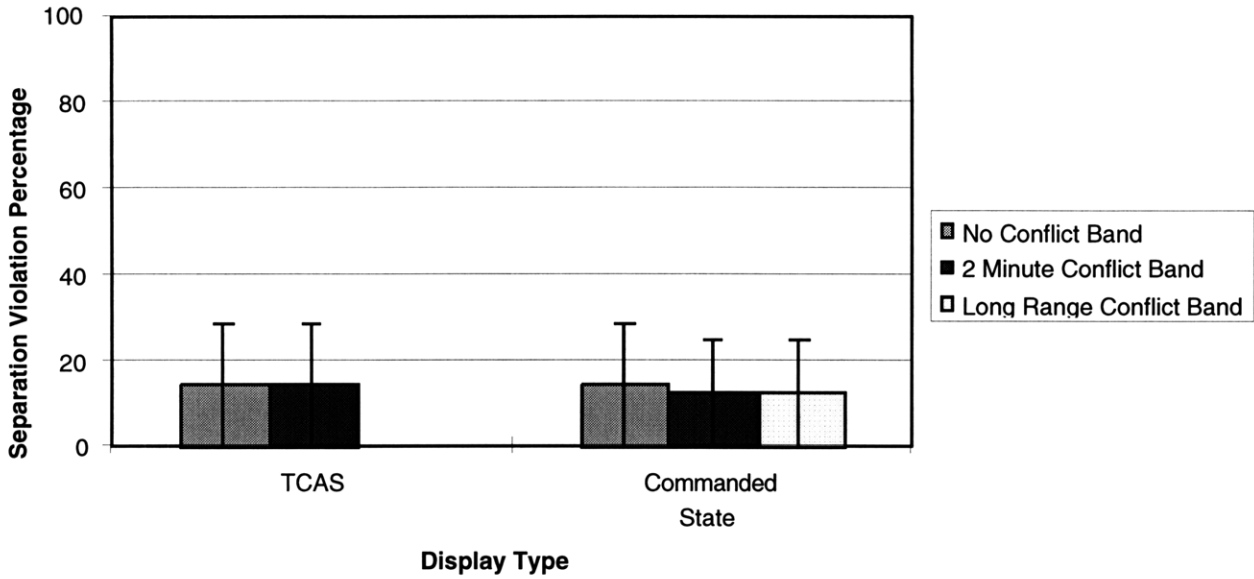
Figure 3.15: Long Range Conflict Scenario, Separation Violation Percentage vs. Display Option

As shown in Figure 3.16, pilots maneuvered significantly earlier with the Commanded State Display ($p < 0.05$). A trend is also observed toward earlier maneuvers with the long range conflict band.
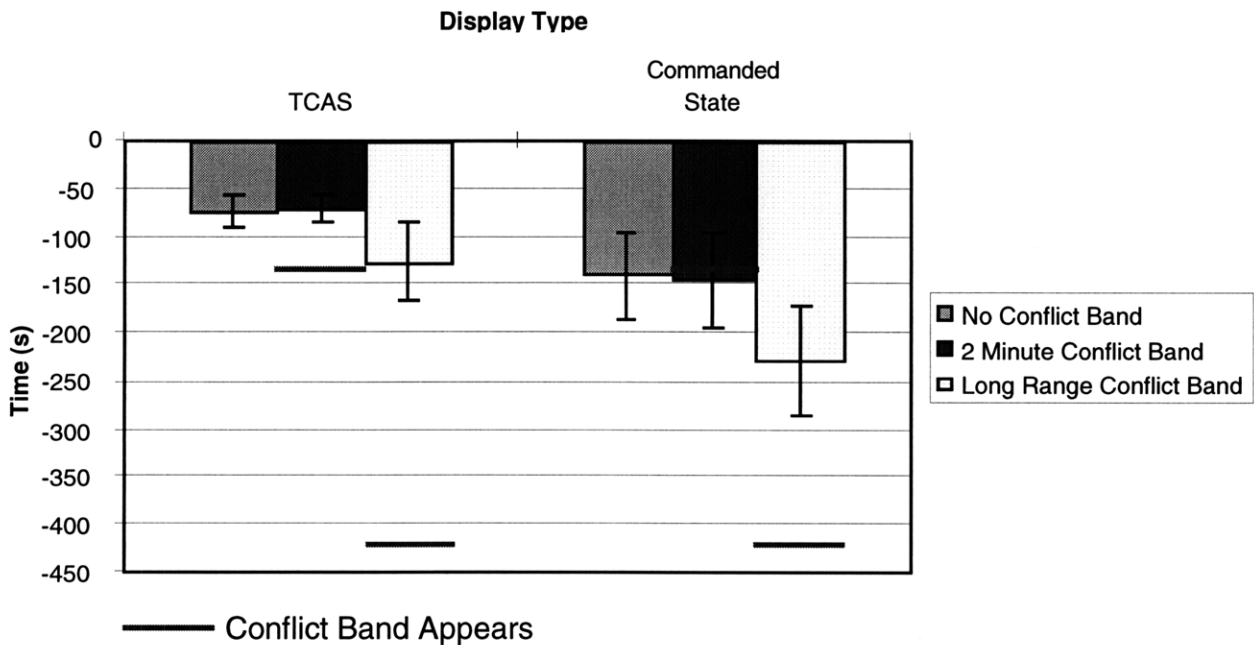
Figure 3.16: Long Range Conflict Scenario, Maneuver Time Before Separation Violation

The presence of either the conflict bands or displayed intent information appeared to alert pilots to the conflict earlier, however this advance notice had little affect on their ability to avoid the conflict.

3.4.4   Subjective Results

An AHP analysis was performed on all display options and is shown in Figure 3.17.
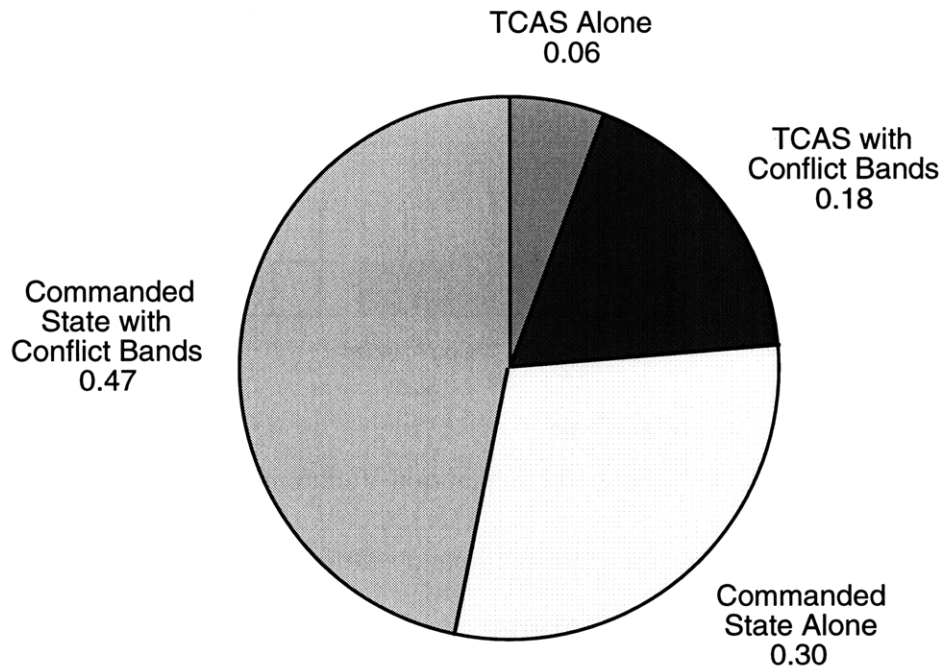
Figure 3.17: Pilot Display Preference

Pilots preferred all display options over the base TCAS Display by at least a 3:1 margin. They tended to prefer the Commanded State Display with Conflict Bands 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.

Pilots were asked to indicate which display options were too cluttered. These results are provided in Figure 3.18.
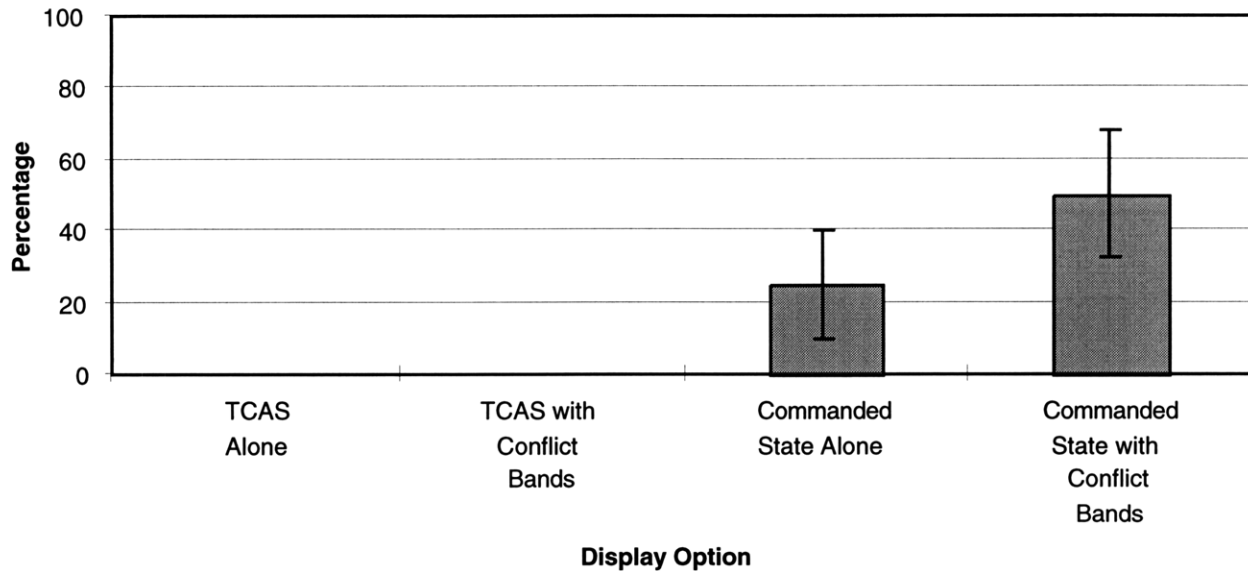
Figure 3.18: Percentage of Pilots Indicating Display Was Too Cluttered

Although pilots preferred the Commanded State Display, particularly with the conflict bands, they found the display to be overly cluttered in certain situations. Problems with overlaid symbology and intent information shown for non-conflicting aircraft were mentioned. Another contributing factor could be the addition of the commanded altitude to the plan view display. As noted previously, pilots did not have the option of selecting or deselecting intent information with the Commanded State Display as they had in Experiment 1.

Pilots' ratings for the value of information elements shown on the displays is given in Figure 3.19.
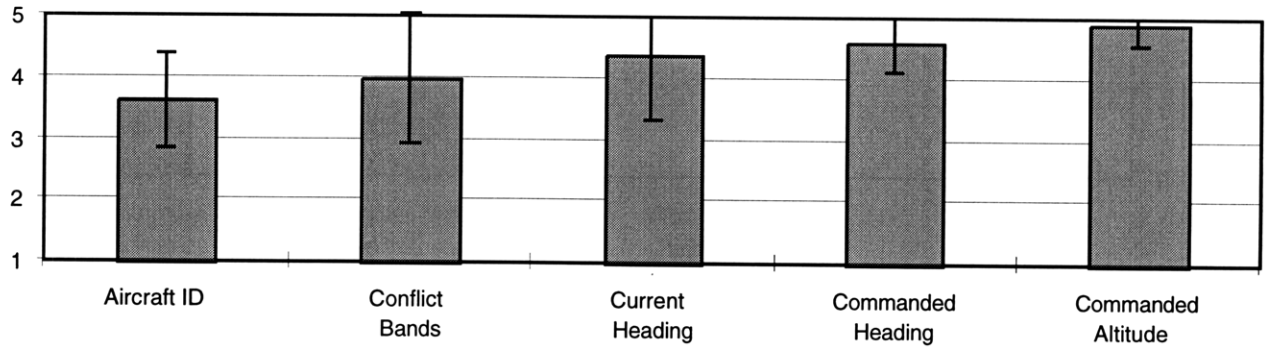
Figure 3.19: Value of Information Elements

Pilots rated all of the information elements to be valuable, but rated displayed intent information higher than the conflict bands. Commanded altitude received the highest rating, with 7 out of 8 pilots rating it "very valuable".

When asked what the maximum range in miles or minutes should be for showing conflicts, pilots gave answers ranging from 10 to 40 miles and 1.5 to 5 minutes. Some gave varying ranges depending on the traffic density. Three pilots mentioned that all conflicts should be shown within the range indicated, four preferred to see only the nearest one or two conflicts, and one wanted to see the nearest 5 to 7 conflicts.

3.5 Discussion

Separation violations were reduced by almost the same amount over the base TCAS Display when intent information was either displayed directly or incorporated into a conflict probe. When displayed intent and conflict bands were used in combination, there was little improvement in separation violations over cases where they were provided individually, although pilots preferred the combined Commanded State with Conflict Bands Display.

As with Experiment 1, there were fewer separation violations when pilots maneuvered earlier, within several minutes of the conflict. The addition of either displayed intent or conflict bands both led to earlier maneuvers. Pilots tended to maneuver faster in response to a conflict band when using the Commanded State Display. The displayed intent information appeared to complement the conflict band, encouraging pilots to maneuver soon after the conflict band was issued.

Separation violation percentage was similar between the two minute and long range look-ahead conflict bands. For the conflicts used in this experiment, there seemed to be no additional benefit to alerting to conflicts beyond two minutes. In addition, pilots waited much longer to maneuver after a long range conflict band was issued when compared to their response to a two minute band. This result suggests that pilots may have felt that the long range alert was issued too early.

A limited comparison showed that pilots performed as well with the plan view display alone as they had in Experiment 1 with the combined plan/profile view display. This comparison only considered the results for the Commanded State Display on the Intruder Overtake Scenario.

Pilots found the commanded altitude to be more valuable in conflict recognition and avoidance than any other piece of intent information. Their ability to use this information seems to be supported by their significantly better performance with the Commanded State Display on the vertical conflict, Intruder Overtake Scenario.

Chapter 4

Conclusions

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 basic TCAS Display.

The Commanded State Display led to the best overall performance on the two experiments. In the first experiment, pilots performed as well with the Commanded State Display as they had 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 rated the current heading, commanded heading, and commanded altitude as "somewhat valuable" or "very valuable".

A two minute look-ahead time for conflict bands appears to be sufficient in alerting pilots to conflicts in these two experiments. In the second experiment, pilots performed as well with the two minute conflict band as they did with the long range band. Also, most of the reduction in separation violation percentage occurred for maneuvers performed within two minutes of the conflict. In practice, varying workload conditions and differences in the flight environment would likely have an influence on the most desirable time to alert. Different look-ahead times may be needed for terminal and en-route operations.

Many additional display issues will need to be carefully examined before intent information can be incorporated into a CDTI. Symbology must be tuned to fit into the small traffic displays common in current commercial airline cockpits. Strategies to prevent information overload, especially in time critical situations will need to be considered. 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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Appendix A Experiment 1 Pilot Briefing

AT TABLE

- Future datalink systems will likely be able to pass current state and intent information between planes.

- Experiment being conducted to test 4 different prototype traffic displays, based on the TCAS system.

- Displays emphasize different elements of intent information.

- Experimental scenarios take place in a free flight-like environment, near a terminal area.

- No rules or procedures have yet been established for free flight.

- Since free flight is assumed, no rules concerning odd/even altitudes for east/west travel, no set procedures (SID's, STAR's) for entering or leaving the terminal area.

- During experiment, pilots are responsible for maintaining their own traffic separation - no ATC.

- Pilots are free to maneuver at any time, but must maintain minimum separation of 2 nm. laterally or 500 ft. vertically from all other traffic.

- All intruder aircraft fly in LNAV/VNAV mode, but the amount of information shown about their trajectories is varied.

- In each scenario, pilot will be cleared direct to a VOR (the only navigation fix shown on the EHSI).

- Unless necessary to avoid a traffic conflict, pilot should fly direct to the VOR, level at the initial altitude of 18000 ft..

- As soon as a conflict is resolved, pilot should turn direct to the VOR and return to 18000 ft.

- Pilot may maneuver the aircraft in any way necessary to avoid other traffic except for increasing the aircraft's speed.

- Goals of each scenario are:
  1. Maintain the minimum traffic separation (most important).
  2. Arrive at the VOR as quickly as possible, without increasing speed.
  3. Turn direct to the VOR and return to 18000 ft. as soon as a conflict is resolved.

- In addition to maneuvering to avoid the conflict, the pilot should indicate when a potential conflict is identified. This is done by pushing the left button on the sidestick. The button should be pushed when the pilot perceives a threat which he/she thinks will require an avoidance maneuver.

-    Pilot should tell experimenter which airplane has been identified as a potential conflict and which airplane he/she is maneuvering to avoid.

-    Pilot will fly 5 different traffic scenarios for each display.

-    Practice time will be allotted for each display prior to running scenarios for that display. Practice should continue until the subject is comfortable with the displays and simulator.

-    General information about displays.
     - Show TCAS Display.
     - Traffic information is superimposed on EHSI and uses TCAS symbology.
     - Aircraft ID printed next to airplane symbol (can be used for identification purposes when pushing sidestick buttons).
     - TCAS TA's and RA's given for all displays.
     - No wind in any scenarios, so track = heading.

-    Will have summary sheet available next to simulator.

AT SIMULATOR

-    Simulator:
     - Primary Flight Display.
     - TCAS Traffic Display.
     - Keyboard buttons (start, stop, zoom in/zoom out).
     - Sidestick with 4 buttons (only 3 used):
          - Left button: conflict identified.
          - Right button: disengage autopilot.
          - Trigger button: engage autopilot.
     - B-737 MCP.
     - CDU (not used).
     - Dynamics- similar to B-737.

-    Pilot may fly the aircraft manually or with autopilot (altitude, heading, speed, vertical speed - no LNAV or VNAV), whichever is preferred.

-    Show and review task summary sheet.

PRACTICE SCENARIOS

-    Practice scenarios can continue until pilot comfortable with displays, simulator.

-    Practice scenario with TCAS.

-    Practice scenario with first display.

-    Emphasize practice with:
     - Conflict identification.
     - Manual and MCP control.
     - Information toggles.

Appendix B   Experiment 1 Pilot Questionnaire

Background

Age _____

Total Flight Hours _____   Hours in Airplanes _____

Military Flight Experience (Y/N) _____

Hours in Glass Cockpit Airplanes _____   Hours in TCAS Equipped Airplanes _____

Aircraft Certificates and Ratings _____

_____

Aircraft Flown and Position (Captain, 1st, or 2nd Officer) _____

_____

TCAS Questions

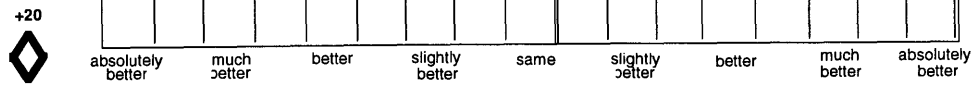What is your opinion of TCAS? _____

_____

Do you ever use the TCAS traffic display for purposes other than collision avoidance?

_____

_____

How many RA's have you had? _____

Have you ever had a problem with TCAS? If so, did the problem create a hazardous situation?
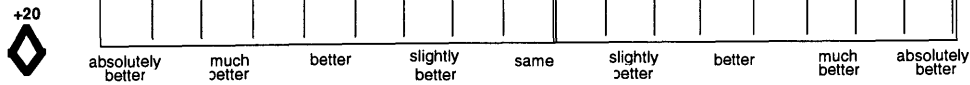
_____
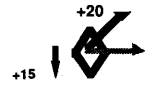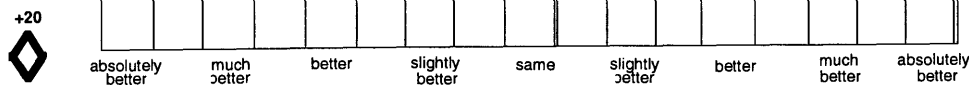
_____

1. Which is the better display?

TCAS Display ... **Rate Display**

| absolutely better | much better | better | slightly better | same | slightly better | better | much better | absolutely better |

TCAS Display ... **Commanded State Display**

| absolutely better | much better | better | slightly better | same | slightly better | better | much better | absolutely better |

TCAS Display ... **FMS-Path Display**

| absolutely better | much better | better | slightly better | same | slightly better | better | much better | absolutely better |

Rate Display ... **Commanded State Display**

| absolutely better | much better | better | slightly better | same | slightly better | better | much better | absolutely better |

Rate Display ... **FMS-Path Display**

| absolutely better | much better | better | slightly better | same | slightly better | better | much better | absolutely better |

Commanded State Display ... **FMS-Path Display**

| absolutely better | much better | better | slightly better | same | slightly better | better | much better | absolutely better |

2. Please rate each information element for its value in resolving traffic conflicts. Consider the displays where the information was available.

Aircraft ID

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

Conflict Bands

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

Current Heading

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

Altitude Rate

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

Commanded Heading

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

Commanded Altitude

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

FMS Flight Plan

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

97

3. The profile view display made me more aware of the traffic situation in the vertical plane.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

4. I could get vertical information as easily from the EHSI as I could from the profile view display.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

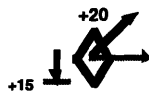5. Please check any displays that were too cluttered.
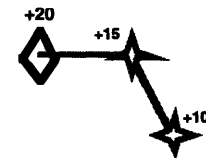
TCAS Display

Rate Display

Commanded State Display

FMS-Path Display

6. What was your strategy for avoiding traffic conflicts? Did it change with the display?

7. When did you decide to turn on an intruder's information?

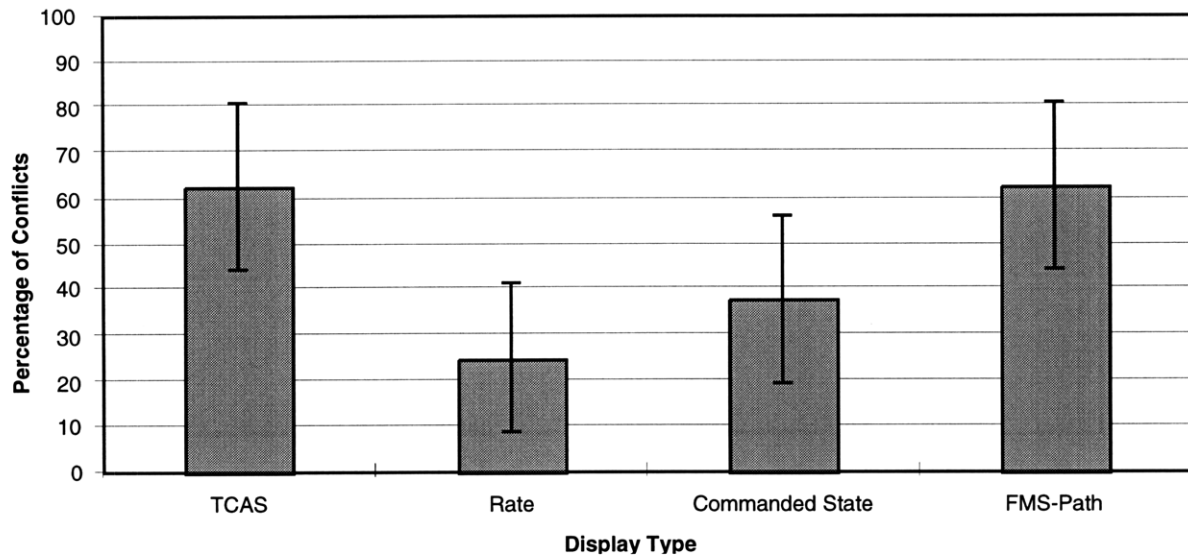8. What information should be added to the displays?

9. What information was unnecessary?

10. Do you have any additional comments or suggestions? (Please use back if necessary.)

Appendix C   Experiment 1 Scenario Specific Results

Scenario 1
Intruder Overtake

Separation Violations

Maneuver Time Before Separation Violation
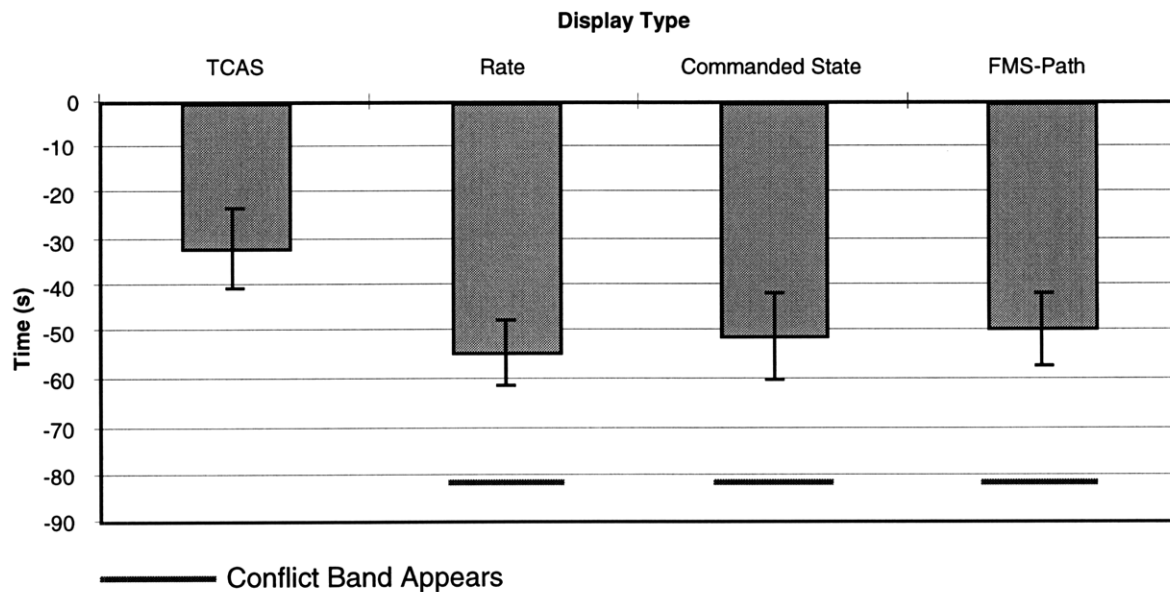
Scenario 2
Intruder Trajectory Change

Separation Violations

Percentage of Conflicts (y-axis: 0 to 100)

Display Type (x-axis: TCAS, Rate, Commanded State, FMS-Path)

Maneuver Time before Separation Violation

Display Type

Time (s) (y-axis: 0 to -200)

TCAS   Rate   Commanded State   FMS-Path

——— Conflict Band Appears
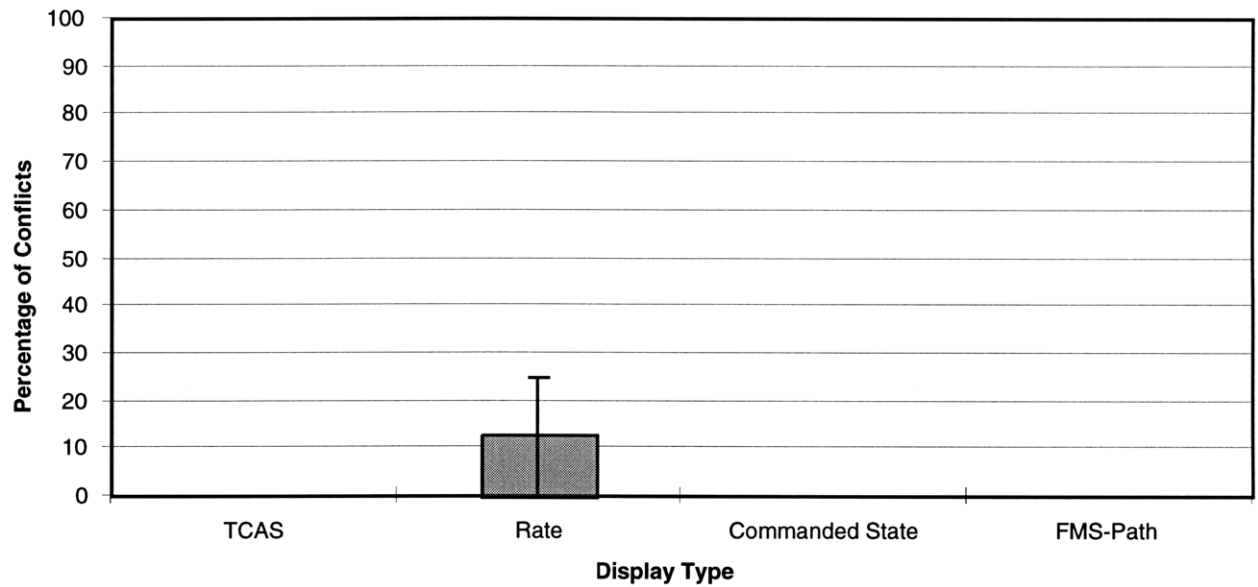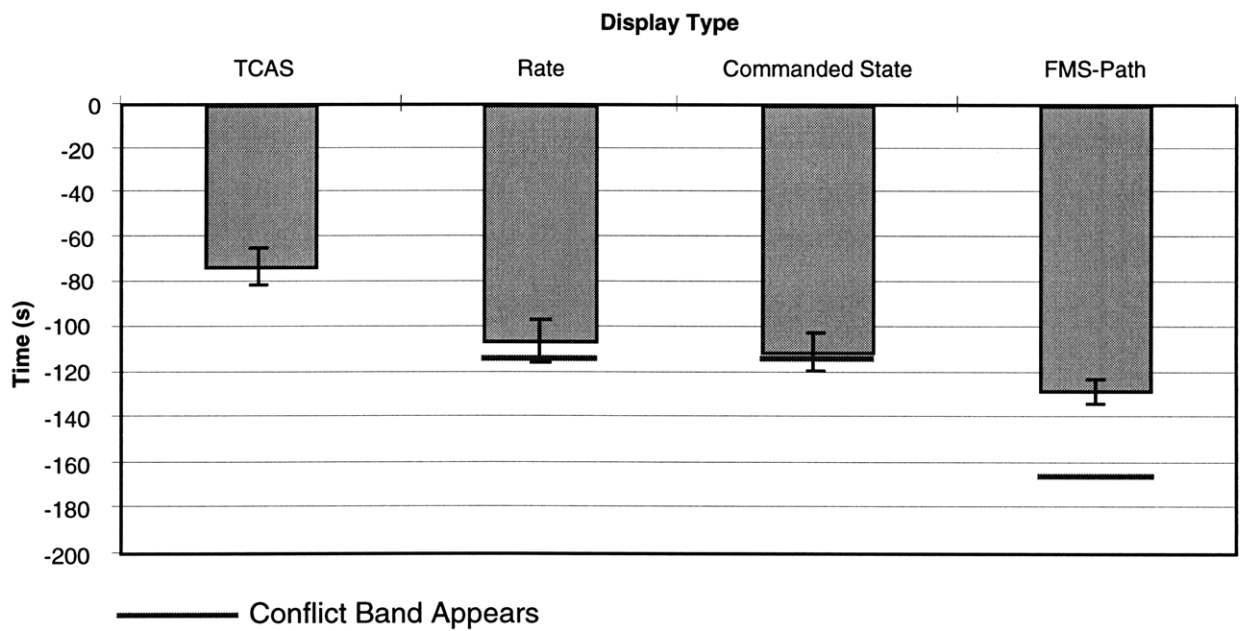
Scenario 3
Ownship Overtake
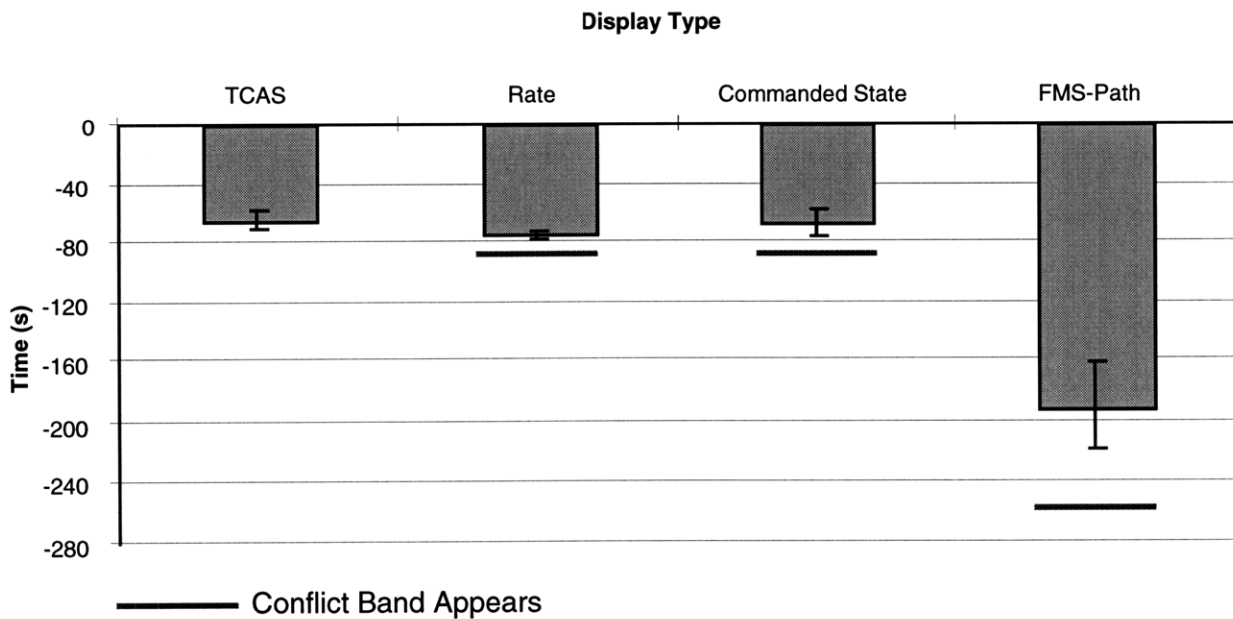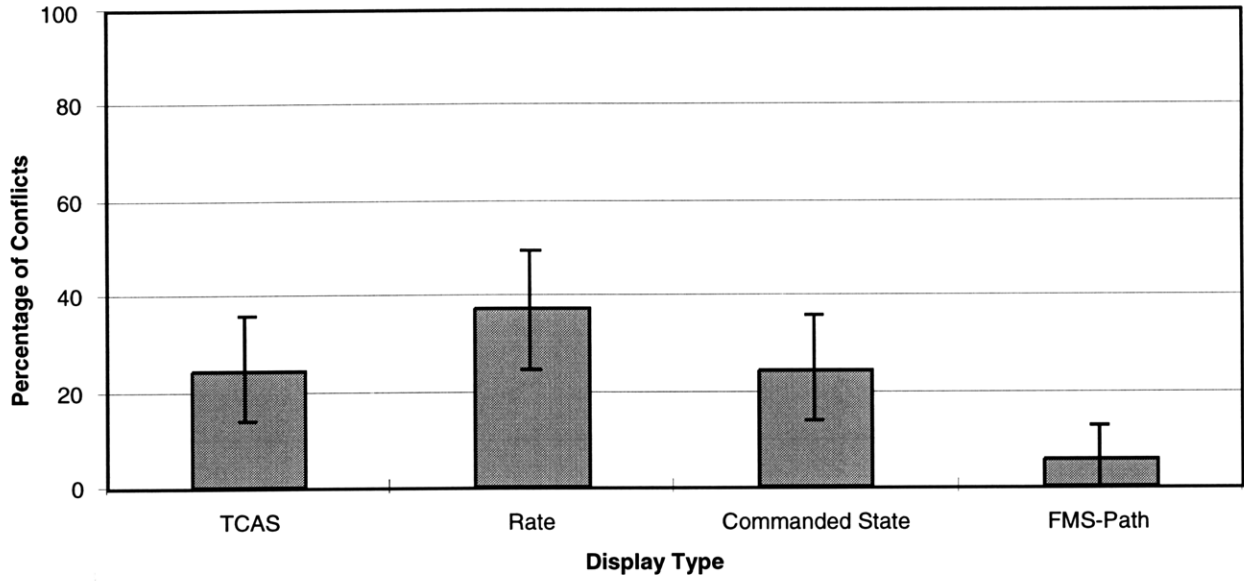
Separation Violations

Maneuver Time before Separation Violation

101
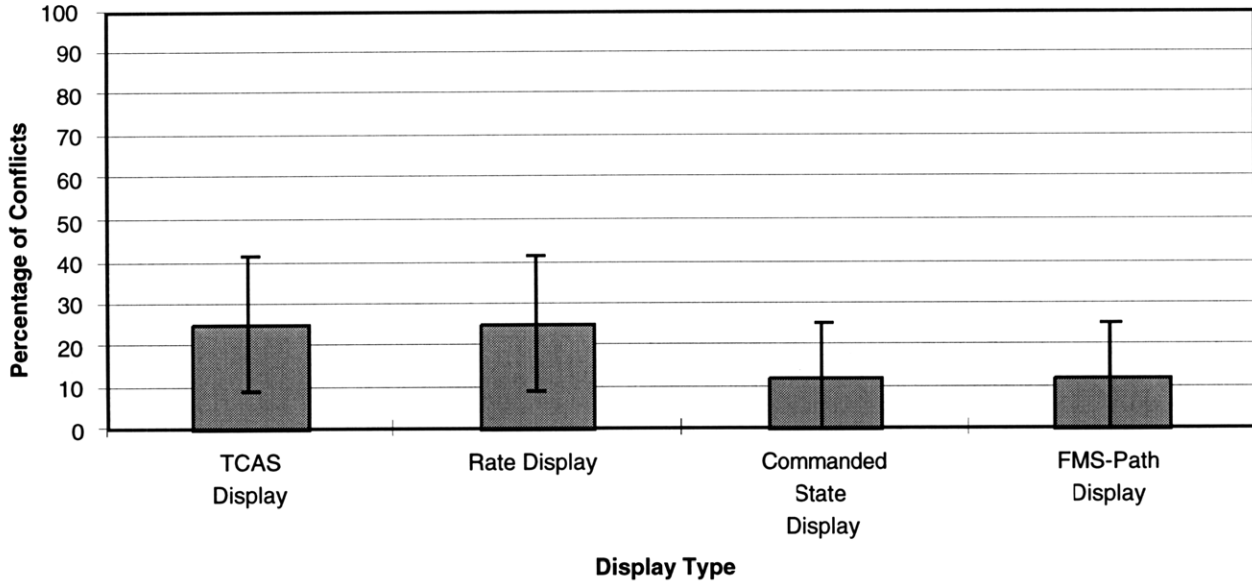
Scenario 5
Dual Conflict

Separation Violations

Maneuver Time Before Separation Violation

—— Conflict Band Appears
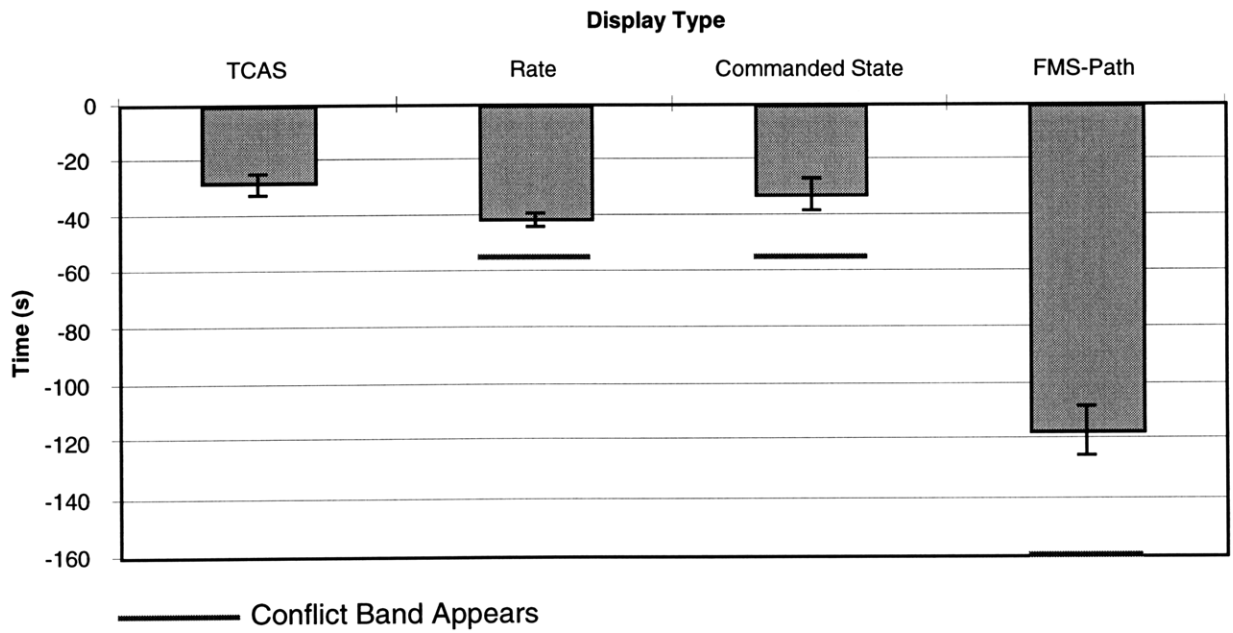
Appendix D   Experiment 2 Pilot Briefing

AT TABLE

- Future datalink systems will be able to pass current state and intent information between planes.

- Experiment being conducted to test several prototype traffic displays, based on the TCAS system.

- Displays represent varying amounts of information available about intruder aircraft in addition to different ways of presenting the information.

- Experimental scenarios take place in a free flight-like environment, near a terminal area.

- No rules or procedures have yet been established for free flight.

- Since free flight is assumed, no rules concerning odd/even altitudes for east/west travel, no set procedures (SID's, STAR's) for entering or leaving the terminal area.

- During experiment, pilots are responsible for maintaining their own traffic separation - no ATC.

- Pilots are free to maneuver at any time, but must maintain minimum separation of 2 nm. laterally or 500 ft. vertically from all other traffic.

- In each scenario, pilot will be cleared direct to a VOR (the only navigation fix shown on the EHSI).

- Unless necessary to avoid a traffic conflict, pilot should fly direct to the VOR, level at the initial altitude of 18000 ft..

- As soon as a conflict is resolved, pilot should turn direct to the VOR and return to 18000 ft.

- Pilot may maneuver the aircraft in any way necessary to avoid other traffic except for increasing the aircraft's speed.

- Goals of each scenario are:
  1. Maintain the minimum traffic separation (most important).
  2. Arrive at the VOR as quickly as possible, without increasing speed.
  3. Turn direct to the VOR and return to 18000 ft. as soon as a conflict is resolved.

- In addition to maneuvering to avoid the conflict, the pilot should indicate when a potential conflict is identified. This is done by pushing the left button on the sidestick. The button should be pushed when the pilot perceives a threat which he/she thinks may require an avoidance maneuver.

- Pilot should tell experimenter which airplane has been identified as a potential conflict and which airplane he/she is maneuvering to avoid.

-     General information about displays.
  - Show TCAS Display.
  - Traffic information is superimposed on EHSI and uses TCAS symbology.
  - Aircraft ID printed next to airplane symbol (can be used for identification purposes when pushing sidestick buttons).
  - TCAS TA's and RA's given for all displays.
  - No wind in any scenarios, so track = heading.

-     Will have summary sheet available next to simulator.

AT SIMULATOR

-     Simulator:
  - Primary Flight Display.
  - TCAS Traffic Display.
  - Keyboard buttons (start, stop, zoom in/zoom out).
  - Sidestick with 4 buttons (only 3 used):
    - Left button: conflict identified.
    - Right button: disengage autopilot.
    - Trigger button: engage autopilot.
  - B-737 MCP.
  - CDU (not used).
  - Dynamics- similar to B-737.

-     Subject may fly the aircraft manually or with autopilot (altitude, heading, speed, vertical speed - no LNAV or VNAV), whichever is preferred.

-     Show and review task summary sheet.

PRACTICE SCENARIOS

-     Practice scenarios can continue until pilot comfortable with displays, simulator.

-     Practice scenario with TCAS.

-     Practice scenario with first display.

-     Emphasize practice with:
  - Conflict identification.
  - Manual and MCP control.

Appendix E   Experiment 2 Pilot Questionnaire

Background

Age _____

Total Flight Hours _____   Hours in Airplanes _____

Military Flight Experience (Y/N) _____

Hours in Glass Cockpit Airplanes _____   Hours in TCAS Equipped Airplanes _____

Aircraft Certificates and Ratings _____

_____

Aircraft Flown and Position (Captain, 1st, or 2nd Officer) _____

_____

TCAS Questions

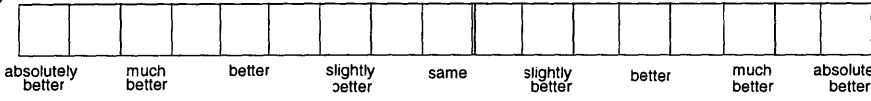What is your opinion of TCAS? _____

_____

Do you ever use the TCAS traffic display for purposes other than collision avoidance?

_____

_____

How many RA's have you had? _____

Have you ever had a problem with TCAS? If so, did the problem create a hazardous situation?
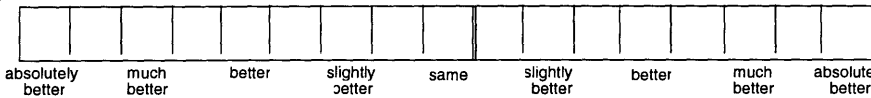

_____

_____

1. Which is the better display?
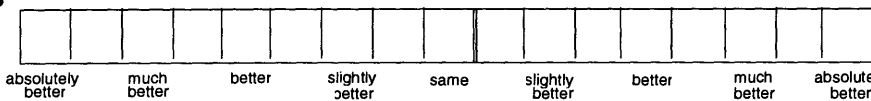
Basic TCAS

**Basic TCAS
with Conflict Bands**
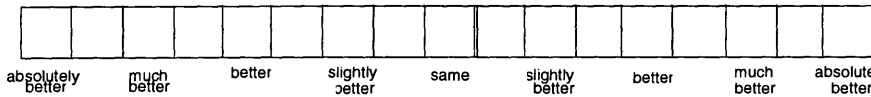
+20

absolutely better · much better · better · slightly better · same · slightly better · better · much better · absolutely better

+20

Basic TCAS

Enhanced TCAS

+20

absolutely better · much better · better · slightly better · same · slightly better · better · much better · absolutely better

+20

Basic TCAS

**Enhanced TCAS
with Conflict Bands**

+20

absolutely better · much better · better · slightly better · same · slightly better · better · much better · absolutely better

+20

**Basic TCAS
with Conflict Bands**

Enhanced TCAS

+20

absolutely better · much better · better · slightly better · same · slightly better · better · much better · absolutely better

+20

**Basic TCAS
with Conflict Bands**

**Enhanced TCAS
with Conflict Bands**

+20

absolutely better · much better · better · slightly better · same · slightly better · better · much better · absolutely better

+20

Enhanced TCAS

**Enhanced TCAS
with Conflict Bands**

+20

absolutely better · much better · better · slightly better · same · slightly better · better · much better · absolutely better

+20

106

2. Please rate each information element for its value in resolving traffic conflicts. Consider the displays where the information was available.

Aircraft ID

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

Conflict Bands

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

Current Heading

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

Commanded Heading

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

Commanded Altitude

Very Detrimental	Somewhat Detrimental	Neutral	Somewhat Valuable	Very Valuable

3. Please check any displays that were too cluttered.

Basic TCAS

+20

**Basic TCAS
with Conflict Bands**

+20

_____

_____

Enhanced TCAS

+20

**Enhanced TCAS
with Conflict Bands**

+20

_____

_____

4. Did your strategy for avoiding conflicts change with the addition of the heading arrows? With the addition of the conflict bands? If so, how?

5. What is the maximum range or time that a conflict band should appear?
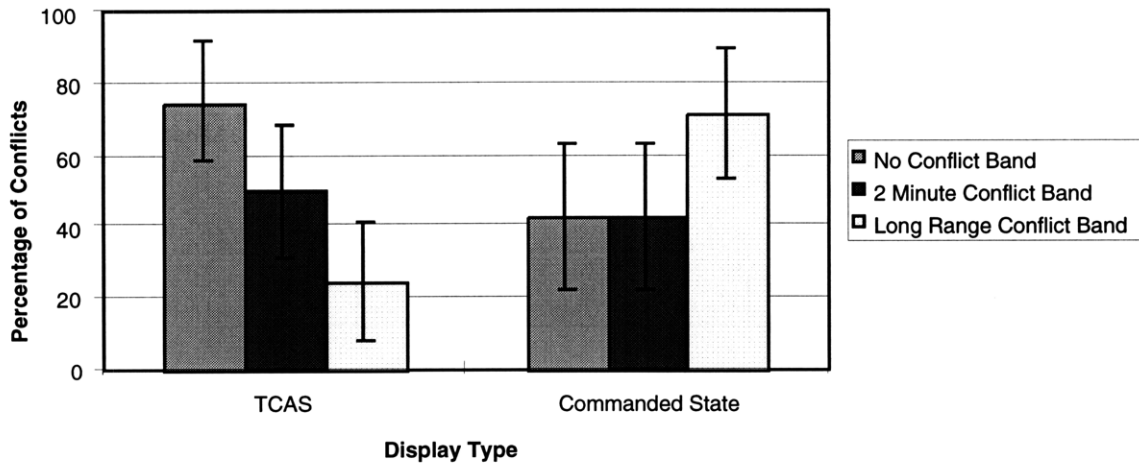
6. What is the maximum number of conflicts it is useful to show or should all conflicts be shown within the range indicated above?
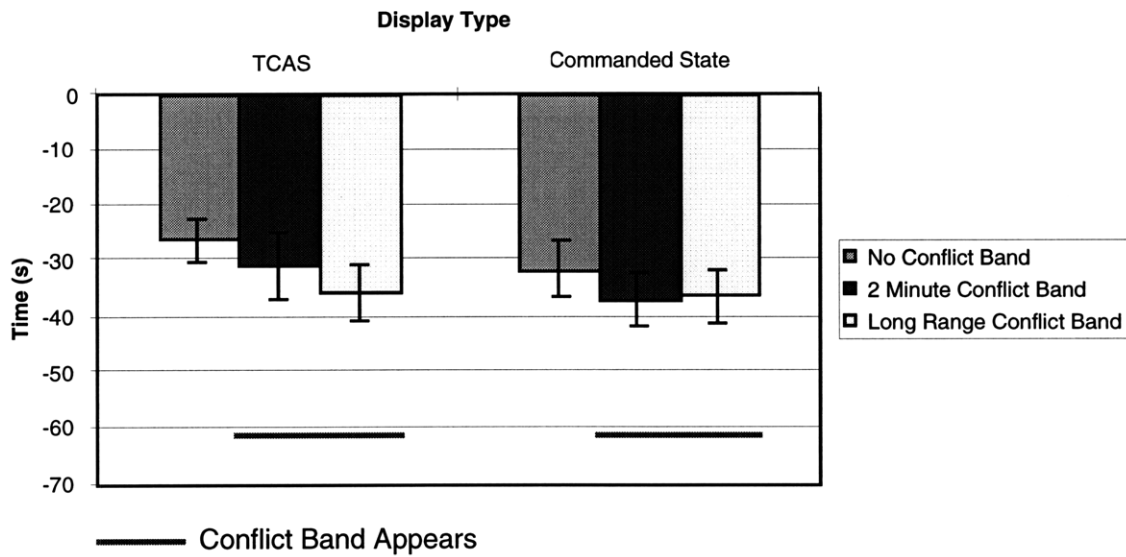
7. Do you have any additional comments or suggestions?

Appendix F Experiment 2 Scenario Specific Results

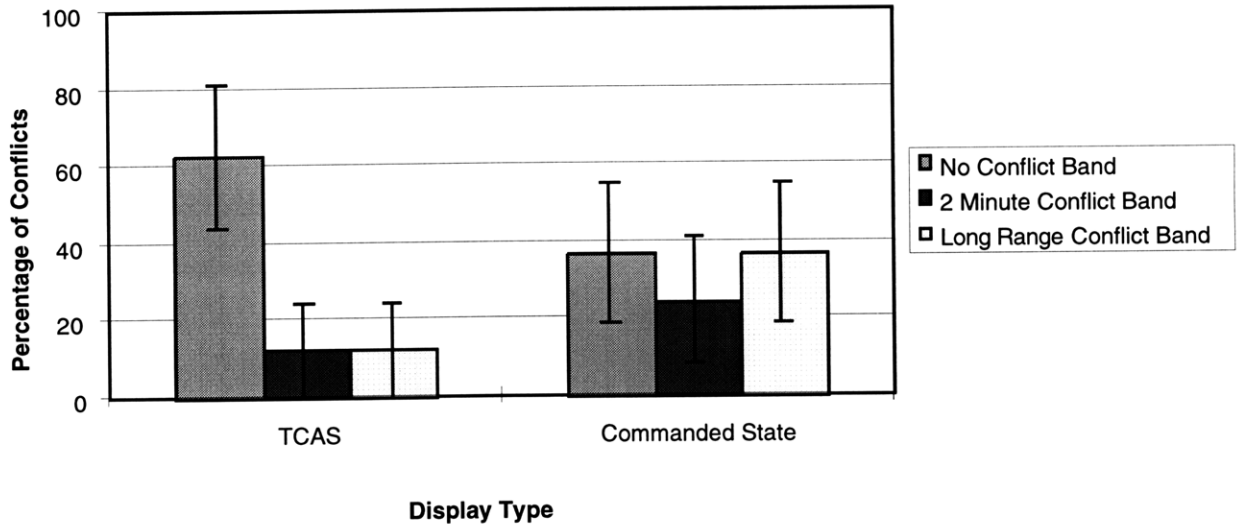## Scenario 1
Short Range Conflict

Separation Violations

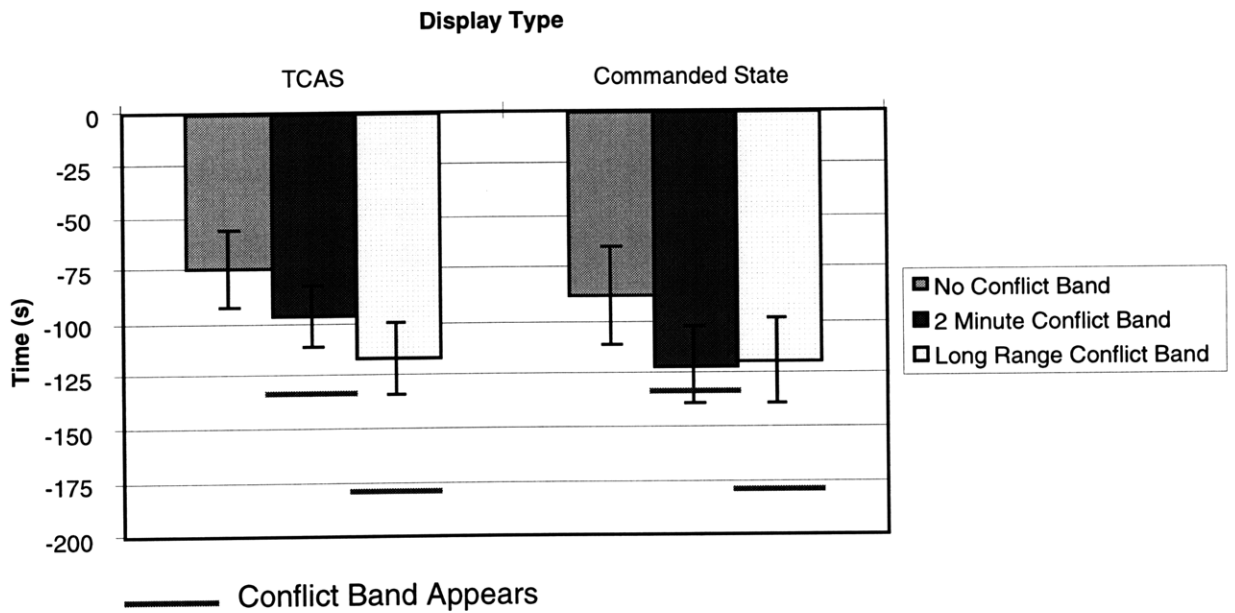

Maneuver Time Before Separation Violation

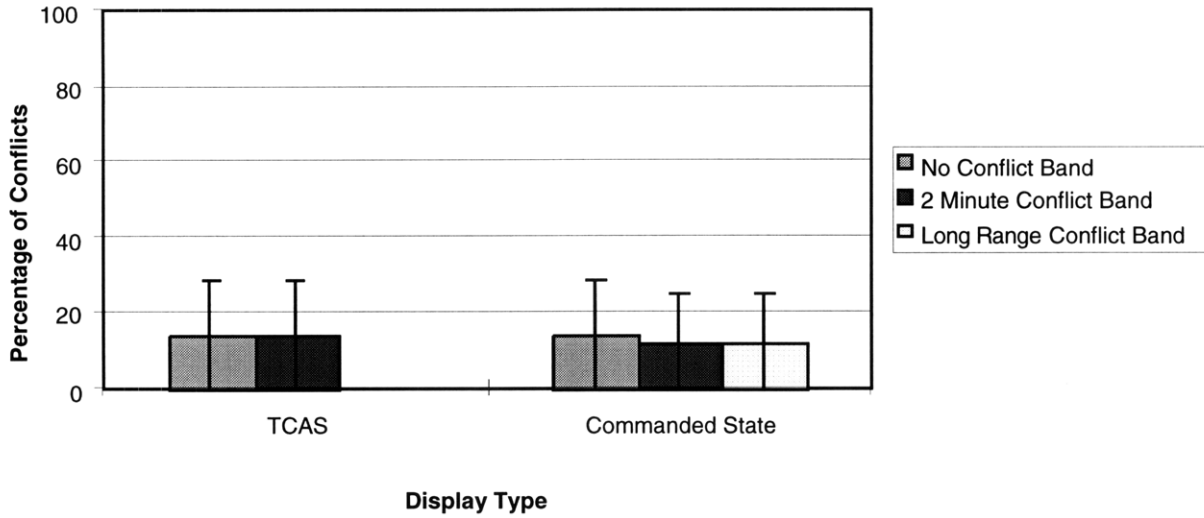# Scenario 2
Intruder Maneuvers During Conflict

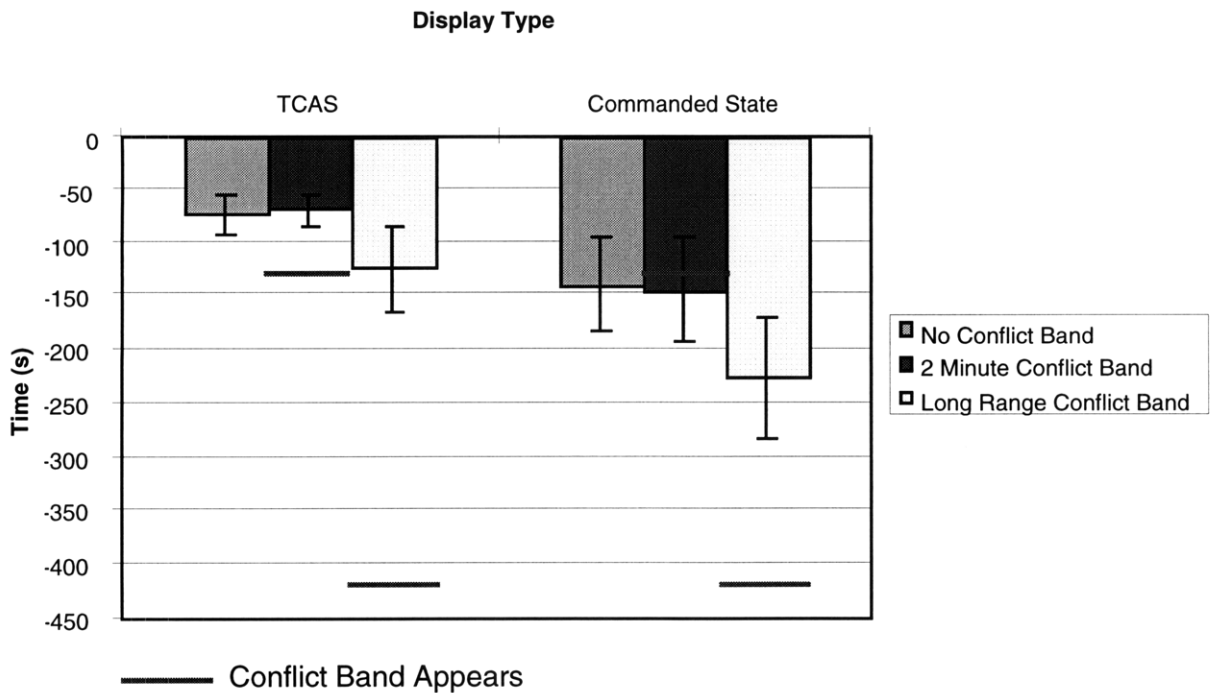## Separation Violations

Maneuver Time Before Separation Violation

Scenario 3
Long Range Conflict

Separation Violations

Percentage of Conflicts vs Display Type (TCAS, Commanded State), with legend: No Conflict Band, 2 Minute Conflict Band, Long Range Conflict Band

Maneuver Time Before Separation Violation

Time (s) vs Display Type (TCAS, Commanded State), with legend: No Conflict Band, 2 Minute Conflict Band, Long Range Conflict Band; Conflict Band Appears
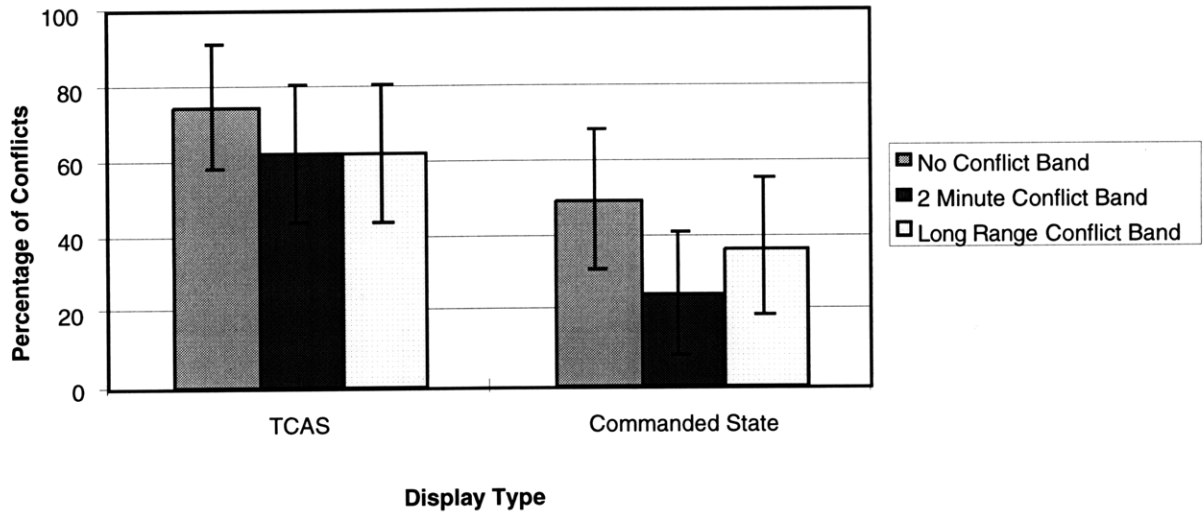
Scenario 4
Intruder Overtake

Separation Violations

Maneuver Time Before Separation Violation