

IMPACT OF TRAFFIC SYMBOL DIRECTIONAL CUES ON PILOT PERFORMANCE DURING TCAS EVENTS

Wes Olson

Massachusetts Institute of Technology Lincoln Laboratory, Lexington, MA

Bill Kaliardos

Federal Aviation Administration, Washington, DC

Michael Zuschlag and Andrew Kendra

*United States Department of Transportation Volpe National Transportation Systems Center
Cambridge, MA*

Abstract

Implementation of Automatic Dependent Surveillance – Broadcast (ADS-B) technology enables aircraft to broadcast, receive and display a number of aircraft parameters that were not previously available to pilots. While significant research has been conducted regarding Cockpit Display of Traffic Information (CDTI) display format, there is little research to assess the impact this additional information would have on pilot response to Traffic Alert and Collision Avoidance System II (TCAS II) Traffic Advisory (TA)/Resolution Advisory (RA) events.

The purpose of this study is to determine the impact of providing directionality information for traffic symbols on a TCAS traffic display during a TA/RA event. This issue is particularly relevant for shared TCAS/CDTI displays. The study supported the development of CDTI performance standards through RTCA, Inc.

Twenty-three current and qualified Boeing 737 (B737) pilots flew two 35-minute flight segments in a full motion B737 Next Generation (NG) flight simulator, one flight segment with modified symbology that included traffic directionality information and one with standard TCAS symbology that does not directly provide directionality information. During each flight segment, pilots experienced six separate TA/RA encounters that were counter-balanced to vary encounter geometry, phase of flight and visual conditions. Of the 276 planned RA encounters, 251 RAs actually occurred. In some cases, no RA was received due to either pilot

maneuvering (22 cases) or simulator issues (three cases). Dependent measures included pilot responses to TCAS TA/RA encounters and pilot use of TCAS displays as measured by eye tracking data.

The results indicate that inclusion of traffic directional information on a traffic display during TCAS TA/RA encounters does not negatively affect pilot response to RAs as measured by timing and magnitude of the RA response. Directional information also yielded no observed effect on pilot scans (allocation of gaze).

Although effect of symbology was not observed, horizontal and/or vertical maneuvering beyond that commanded by the RA was observed in 90 of 273 possible TCAS TA/RA encounters, independent of symbology. Such maneuvering may be appropriate, depending on the information and context. However, eye tracking and subjective data suggest the maneuvering decisions may be based on the traffic display and not based on visual acquisition or other information. While the overall RA compliance rate was high, the degree of vertical and horizontal maneuvering during the TA/RA event should be better understood since TCAS traffic displays are not intended to support maneuvering. Further research is required to better understand the circumstances in which maneuvering occurs and the resulting impact on the air traffic system.

Introduction

The airborne Traffic Alert and Collision Avoidance System II (TCAS II) provides pilots with a visual display of nearby traffic and two levels of alerts—Traffic Advisories (TAs), which are intended

Submitted for Publication to the 28th Digital Avionics Systems Conference October 25-29, 2009, Orlando, FL

to facilitate visual acquisition of traffic that may pose a flight hazard, and Resolution Advisories (RAs), which provide vertical guidance to avoid aircraft that are projected to be an imminent hazard. This study only considered TCAS II, hereafter referred to as TCAS. TCAS I, a similar system that does not provide RAs, was not considered in this study.

TAs are provided 20 to 48 seconds prior to closest point of approach, while RAs are provided 15 to 35 seconds prior to closest point of approach. Current TCAS traffic displays only depict the relative location of traffic; information regarding relative motion is not directly provided, but must instead be derived by observing the motion of traffic over time. The introduction of ADS-B allows aircraft to broadcast, receive and display a number of aircraft parameters that may be used to improve operations. In particular, velocity vector information may be used to directly display traffic symbol “directionality” (ground track angle) information on a Cockpit Display of Traffic Information (CDTI). While this information may provide valuable cues as to the relative motion of other aircraft, research was needed to determine if use of this directionality information may interfere with desired pilot response to TCAS advisories.

The purpose of the traffic display and the TCAS TA are to assist pilots in visually acquiring traffic that may pose a mid-air collision threat and to prepare for a potential RA. Pilots are specifically prohibited from maneuvering based solely on the traffic display [1]. Pilots are expected to respond to RAs within 5 seconds, and are provided with both an auditory RA alert as well as a visual indication of the commanded vertical rate. There are several types of RAs, including preventive RAs, which require pilots to merely maintain their existing flight profile, and corrective Climb or Descend RAs, which generally require a climb or descent at 1,500 ft per min. In the United States (US), pilot procedures require pilots to comply with RA guidance unless the pilot feels it is unsafe to comply or the pilot has the intruder aircraft in sight and determines that safe separation can be maintained [1].

Aircraft equipped with the capability to receive ADS-B information may present traffic information beyond that of a standard TCAS display. Since directionality information might be displayed on ADS-B traffic symbols during TCAS TA/RA events,

it is important that presentation of this information does not detract or interfere with pilot performance during these events. Interference with pilot response to TCAS advisories may take two forms. First, directionality information may increase the likelihood that pilots maneuver *prior* to an RA by providing better information on the relative motion of other traffic. Previous research indicates that pilots may use existing symbology to maneuver in response to a TCAS TA [2], and cases have been reported of pilots maneuvering operationally without an RA [3]. Second, directionality information may affect pilot response once an RA is issued. This interference may result if pilots use the directionality information to consider horizontal maneuvers during response to the RA. It is possible that the cognitive and physical activities associated with any horizontal maneuvering may replace or delay the desired vertical response to the RA. Degradation of pilot response to an RA may reduce safety margins, especially in the case of encounters between two TCAS-equipped aircraft. In TCAS-TCAS encounters, the RA maneuvers between the two aircraft are coordinated. Thus non-compliance by one aircraft can result in reduced separation especially if the aircraft maneuver in the same vertical direction. While research has shown that displays depicting additional information such as directionality improve situation awareness [4, 5], no research directly addresses the issue of the potential impact of this information on pilot response to RAs.

This study assessed the impact of traffic directional information by presenting airline pilots in a full motion simulator with a number of TCAS TA/RA encounters, using both standard TCAS traffic symbols as well as modified symbols that presented aircraft directionality information on the same display hardware). Dependent measures included heading and vertical rate changes during the TCAS TA/RA sequence, timing and magnitude of pilot response to the RA as well as eye tracking data on pilot gaze on various cockpit displays during the TCAS TA/RA sequence. These data will provide information on the use of traffic displays during a TCAS TA/RA sequence as well as information regarding any potential impact on pilot response to TCAS TAs and RAs.

This study was conducted to support the Federal Advisory committee that develops standards for ADS-B traffic displays (RTCA SC-186). These

standards have been published by RTCA as DO-317 [6].

Method

Participants

Twenty three current and qualified Boeing 737 (B737) pilots participated in this experiment. The median total flight experience was 12,000 flight hours (range 5,000 to 24,000 hrs) with a mean of 3,000 hrs in this type of aircraft (range 200 to 15,000 hrs). All participants had received initial TCAS training through their airline, and the median flight time with TCAS was 8,000 flight hours (range 200 to 15,000 hrs). All participants were actively flying for a US major airline and received compensation for their participation.

Flight Simulator

The flight simulator used in this study was the Federal Aviation Administration (FAA) Boeing B737-800 Level D full motion flight simulator operated by the Flight Operations Simulation Branch (AFS-440) at the Mike Monroney Aeronautical Center in Oklahoma City, Oklahoma. Aircraft performance data including climb rate, heading, airspeed, control inputs, altitude, and RA type was collected at 5 Hz.

Eye Tracking Equipment

Pilot eye point-of-regard data were recorded using an Applied Science Laboratories (ASL) Mobile Eye head mounted, low-level infrared eye tracking system fitted to the pilot-flying. The system represents eye position as a crosshair icon in a video of the pilot's field of view. For each pilot, this video, along with ambient sounds including TCAS aural alerts, were recorded to digital files in AVI format at 30 Hz. The Mobile Eye product time-stamps each frame of the video.







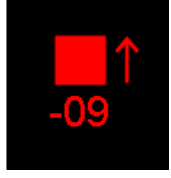

TCAS Traffic Displays

The TCAS traffic symbology was presented on the Navigation Display (ND), while RA guidance was presented on the Primary Flight Display (PFD). Honeywell provided the TCAS and traffic display software, and CAE provided the simulator and

associated software. Table 1 shows a notional depiction of the standard and modified traffic symbology. Note that on the modified symbology, directionality is indicated by the orientation of the arrowhead shape, with the apex indicating the direction of motion.

For both the standard and modified traffic symbols, the arrow to the right of the symbol indicates the direction of vertical motion (when vertical speed exceeds approximately 500 feet per minute), and the number below the symbol indicates the relative altitude difference between the intruder and own aircraft in hundreds of feet (traffic shown in Table 1 is 900 feet below and climbing). The color of standard and modified symbology was identical, and the size was nearly identical (size was slightly adjusted for legibility).

Table 1. Standard and Modified TCAS Symbology

TCAS Symbol State	Standard Symbol	Modified Symbol
Other Traffic		
Proximate Traffic		
Traffic Advisory (TA)		
Resolution Advisory (RA)		

Scenarios

Each pilot flew two flight segments, one with the standard traffic symbols and one with the

modified traffic symbols. The order of flight segments and the display experienced first was counter-balanced between participants. Each flight segment lasted approximately 35 minutes. One flight segment was from Dallas-Fort Worth airport (DFW) to the Oklahoma City airport (OKC). The other flight segment was the reverse, OKC to DFW. Each flight began on the runway ready for takeoff with checklist complete, and was either terminated upon completion of the final RA, or flown to landing, depending upon pilot preference.

The participant was the pilot flying each flight segment. The pilot-not-flying was an FAA staff pilot. The pilot-not-flying was not part of the study and was instructed to perform all normal and requested pilot-not-flying duties to include checklists and radio transmissions. The simulator operator acted as the simulated air traffic controller when required.

The route of flight was a direct Area Navigation (RNAV) route that proceeded from the departure runway to a point near the arrival airport where the pilot received vectors to a visual final approach course.

During each flight segment, each pilot was exposed to six pre-scripted potential TCAS TA/RA encounters. Each of the six RAs occurred in the same order and point during each flight segment, and was generated using simulated traffic on a preplanned trajectory designed to induce an RA. The six planned TA/RA encounters were distributed equally over the phases of flight with two while climbing, two while level, and two while descending. The encounter geometry was also varied so that one occurred while overtaking other traffic while the other five encounters occurred over various approach angles and intruder climb profiles. Additionally, half of the encounters occurred in Instrument Meteorological Conditions (IMC) with flight visibility set to zero (no intruder visible) while the other half of the encounters occurred in Visual Meteorological Conditions (VMC) with eight miles flight visibility. While these encounters were designed to produce a range of RA types, the RA actually received depended upon the specific own-aircraft state and pilot response.

In addition to generated TA/RA traffic, non-advisory traffic was also generated randomly for realism, and as distracters. One, two, or three distracter aircraft were typical.

Procedure

Upon arrival, participants were provided with a brief description of the experiment and the flight task. The participants were told that they were participating in an analysis of pilot scan patterns in glass cockpit aircraft. They were also instructed that during the course of the study they may see some modified symbology; however, the modified symbology was neither discussed nor described. Participants were then introduced to the pilot-not-flying who was an FAA staff pilot. Participants were told that the FAA staff pilot was not a participant in the study. They were given the opportunity to discuss expected duties and procedures for the pilot-not-flying. Participants were allowed to choose either the left or right seat. The FAA staff pilots were instructed to perform as a capable and qualified pilot and comply with all requests by the participant. They were also instructed not to provide any information regarding the modified displays if asked.

Following this overview, participants entered the simulator and the eye tracking device was calibrated by asking pilots to briefly fixate on various portions of the cockpit displays to allow for automatic calibration. Once the eye tracker was calibrated, participants flew a short final approach through landing segment as a warm-up.

Immediately following the warm-up, participants were placed on the end of the runway with checklists complete, ready for take off on the first flight segment. Participants were instructed to fly the routes in accordance with normal company flight procedures and respond to all situations, alerts and cockpit indications as they normally would. In the event that the participant requested an avoidance maneuver or more information regarding potential traffic conflicts, the simulator instructor either replied with "standby" or gave a radio frequency change to the next facility. In no case was the flight crew provided with a clearance to maneuver to avoid any potential conflicts.

Upon completion of the first flight segment, a brief post-flight eye tracker calibration check was conducted, and participants were given a 15 minute break prior to the second flight segment. The procedures for the second flight segment were identical to the first flight segment. For both flight segments, an observer in the jump seat took notes on pilot comments and activities associated with the

TCAS displays, and on pilot responses. Flight simulator data and a video/audio recording of each flight segment were also collected.

Following completion of the second flight segment, a short debrief was conducted to discuss the acceptability and use of the TCAS traffic symbology. Participants were also given a short survey which recorded demographic information and subjective opinions regarding the modified traffic symbology.

Results

The purpose of this study was to assess the impact of providing aircraft directional information on a traffic display during TA/RA events. Data presented in this paper include eye-tracking gaze data, aircraft performance data, subjective reports, and observer notes. The gaze data provided information regarding the extent to which pilots refer to the traffic display versus other locations during the TA/RA event. The aircraft performance data provided an indication of the pilot response to the TA/RA event, and were analyzed for differences associated with traffic symbology. Finally, the subjective reports were used to better understand the relationship between traffic symbology and observed performance.

Eye Tracking Data

The eye-tracking video recording with audio for each pilot was first reviewed to determine the timestamps of each TA, the TA to RA transition, and the Clear of Conflict (COC) advisory for each traffic encounter. These timestamps were used to divide the video for each pilot into 12 data intervals corresponding to each of the six potential traffic encounters divided by alert level within each encounter (TA and RA). The TA interval of each encounter was defined as the interval between the start of the TA indicated by the aural advisory "Traffic, Traffic" and the first aural RA advisory. The RA interval was defined as the interval between the first RA advisory and the COC advisory.

The eye-tracking video of each segment was manually reviewed using video editing software to classify each eye fixation at one of the following five locations:

1. The PFD, which included the TCAS resolution (vertical guidance) information on the attitude and vertical speed indicators.
2. The ND, which included the TCAS traffic display.
3. The out-the-window view.
4. Other areas within the cockpit, such as the Flight Management System (FMS) control display unit and throttle quadrant.
5. Unknown areas, where eye-tracking was lost (e.g., due to calibration problems).

A single fixation was defined as the eye remaining within 50 pixels for at least 100 ms. The location, onset, and end timestamp of each fixation was recorded to a spreadsheet.

For each interval of eye-tracking data, the percent of time gazing at each of the five locations was calculated. Each percentage thus represents the proportion of pilot visual attention at each visual location during the interval, combining average fixation, dwell time, and number of fixations for each location into a single variable¹.

To minimize the impact of missing data due to some pilots having less than six traffic encounters with complete eye-tracking data, the pilots' gaze percentages for the intervals were averaged across traffic encounters for a given symbology (standard versus modified) and visibility (VMC versus IMC). As a result, each pilot had eight data points per location from all combinations of the following:

- Alert Level (TA, RA)
- Symbology (Standard, Modified)
- Visibility (VMC, IMC)

These were used as within-subjects independent variables in a 2×2×2 fully factorized design. Two of the 23 pilots did not have data for every combination of within-subjects independent variables and were dropped from the eye-tracking analyses.

A fourth between-subjects independent variable represented the specific symbology the pilots used on their first flight segment (standard first versus

¹ Analyses for fixation number and average dwell time per fixation at each location were also conducted, but did not yield any fundamentally different results, and are not reported in this paper.

modified first). The percent gaze data were analyzed with a $2 \times 2 \times 2 \times 2/5$ mixed design multivariate analysis of variance (MANOVA) with the percent gaze at the five locations serving as dependent variables.

There was no significant main effect of Symbology (Wilks' $\lambda = 0.712$, $F(4,16) = 1.62$, $p = 0.218$), nor were there any significant interactions with Symbology, except for the four-way interaction of all independent variables (Wilks' $\lambda = 0.546$, $F(4,16) = 3.32$, $p = 0.037$). During RAs, pilots on average tended to look proportionally more at the ND when using the *standard* symbology than the *modified* symbology, but only when under VMC conditions and only for pilots that had the standard symbology on their first leg in the experiment.

Alert Level affected where pilots gazed (Wilks' $\lambda = 0.043$, $F(4,16) = 89.61$, $p < 0.001$), as show in Table 2.

Table 2. Percent of gaze at each location and significance level of difference between TA and RA alerts.

Location	TA	RA	p
ND	48.60%	10.33%	<0.001
PFD	26.25%	76.05%	<0.001
Window	11.48%	3.68%	<0.001
Other	7.53%	1.68%	<0.001
Unknown	6.20%	8.30%	0.263

During a TA, pilots devoted nearly half of their visual attention to the ND with its traffic display. However, during an RA, pilots devoted three-quarters of their attention to the PFD (with its TCAS resolution display) at the expense of all other locations. Pilot attention to the ND on average decreased from 48% during a TA, to 10% during an RA.

Visibility affected pilot gaze patterns (Wilks' $\lambda = 0.250$, $F(4,16) = 11.98$, $p < 0.001$) as shown in Table 3 which depicts gaze over both TA and RA event.

Table 3. Percent of gaze at each location and significance level of difference between VMC and IMC conditions.

Location	VMC	IMC	p
ND	27.25%	31.68%	0.012
PFD	49.48%	52.83%	0.001
Window	10.80%	4.35%	<0.001
Other	5.05%	4.15%	0.253
Unknown	7.45%	7.05%	0.717

Under VMC conditions, pilots spent 10% of their time gazing out the window, while under IMC conditions, they spend 4% of their time gazing out the window, with increases in gaze on the ND and PFD.

There was also a Visibility by Alert Level interaction (Wilks' $\lambda = 0.458$, $F(4,16) = 4.73$, $p = 0.010$), that only affected how much pilots looked out the window as shown in Figure 1 ($F(1,19) = 14.02$, $p = 0.001$).

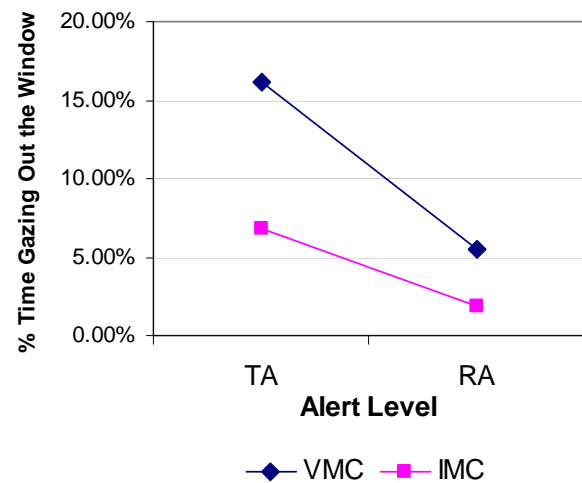


Figure 1. Interaction effect of alert level and visibility conditions on gaze out the window.

During TAs, pilots looked out the window more under VMC conditions than IMC conditions. However during RAs, the amount of VMC out-the-window gaze approached the amount of IMC out-the-window gaze.

Pilot Response to RA Events

Twelve potential TA/RA encounters were planned for each participant, six with the standard symbology and six with the modified symbology for a total of 276 potential RAs. However, due to pilot maneuvering and simulator issues, only 251 RAs occurred. For the standard symbology, 125 RAs were observed with three RAs missed due to simulator issues, and 10 missed due to pilot maneuvering. For the modified symbology, 126 RAs were observed with 12 RAs missed due to pilot maneuvering. Of the 251 observed initial RAs, 80% were Descend RAs, 18% were Climb RAs and the remaining 2% were either Monitor Vertical Speed (MVS) or Adjust Vertical Speed, Adjust (AVSA) RAs.

Pilot response to RAs was analyzed by examination of the magnitude and timing of the RA maneuver. TCAS Climb and Descend RAs require achieving a vertical rate of 1,500 ft/min climb or descent respectively. The commanded vertical rate is somewhat less for MVS and AVSA RAs. For purposes of this study, compliance with the commanded vertical rate was analyzed for the initial RA in an RA sequence using the definitions listed below, with reference to the maximum aircraft vertical velocity observed after the initial RA and prior to RA termination ("Clear of Conflict"):

- Full Compliance – Observed own-aircraft aircraft vertical velocity is in the direction corresponding to the RA, and meets or exceeds the commanded vertical velocity.
- Partial Compliance – Observed aircraft vertical velocity is greater than 0 ft/min in the direction corresponding to the RA, but less than the commanded vertical velocity
- Noncompliance – Observed aircraft vertical velocity is greater than 0 ft/min in a direction opposite to that commanded by the RA

Table 4 contains the results of the analysis of compliance with commanded TCAS vertical rate. The rate of compliance was high and there was no significant difference in compliance due to display symbology ($\chi^2 = 1.01$, $df = 2$, $p = 0.61$). A closer analysis of the one case of noncompliance shows that in this case the pilot received a Descend RA shortly after deciding to initiate a climb in order to avoid the

RA. The pilot continued the existing climb, thus ignoring the RA.

Table 4. Compliance with Commanded TCAS Vertical Rate by Display Symbols.

Compliance	Standard Symbols	Modified Symbols
Full	122	124
Partial	2	2
Noncompliance	1	0
Total	125	126

The timing of RA responses was also analyzed by examining the time between RA initiation and the first definite control column movement in the desired direction. The average response time for RAs using the standard symbology was 1.7 sec, while average response time using the modified symbology was 1.6 sec. This difference was not statistically significant.

Pilot Maneuvering

In addition to the expected pilot maneuvers in response to the RA, pilot maneuvering was also observed in response to the TCAS TA, prior to the RA. All of these maneuvers took place without receiving clearance from Air Traffic Control. These maneuvers were assessed by examining aircraft heading data for lateral maneuvers, and aircraft vertical velocity for vertical maneuvers. In all cases, TCAS TAs occurred while the own aircraft was in a constant heading and without a required change in vertical rate (i.e., either in level flight or during a continuous climb/descent).

An aircraft was considered to have maneuvered horizontally if a heading change of greater than 5 degrees was observed from the time 20 seconds prior to the TA until RA termination. Horizontal maneuvers were observed in 19 of 273 encounters. The median heading change was 25 degrees (range 9 to 49 degrees).

An aircraft was considered to have maneuvered vertically if the aircraft vertical velocity was observed to change greater than 500 ft per minute during the period of 20 seconds prior to the TA until the initial RA. Vertical maneuvering was observed in

77 of 273 encounters. (Vertical and horizontal maneuvering were not mutually exclusive responses, as six cases involved both types of maneuvers, simultaneously).

The cases of vertical maneuvering were further analyzed to assess the potential impact on flight operations. In 68 of the 77 encounters the vertical maneuvering occurred while the aircraft was in an existing climb or descent. Vertical maneuvering in these cases was generally characterized by reducing the existing climb or descent rate, likely in an attempt to avoid the RA. However in four cases, the vertical maneuvering resulted in reversing vertical direction without ATC clearance and another four cases resulted in leveling off without a clearance. In nine of the 77 encounters, the aircraft was in level flight at the time of the TA/RA maneuver. In six of these nine cases, the vertical maneuvering was characterized by initiating a climb or descent shortly before the RA resulting in an altitude deviation of less than 300 feet. In three of the nine cases, the resulting altitude deviation exceeded 300 feet prior to the RA. The observed altitude deviations for these three cases ranged from 500 to 1,200 feet.

Table 5 summarizes the observed maneuvering prior to the RA. Maneuvering prior to the RA was observed in 90 of the 273 potential TCAS TA encounters (33%). There was no effect due to symbology ($\chi^2 = 1.11$, $df = 3$, $p = 0.83$). Maneuvering was observed with 19 of the 23 participants.

Table 5. Maneuvering Prior to the RA by Display Symbol.

Maneuver Prior to RA	Standard Symbols	Modified Symbols
Horizontal	7	6
Vertical	33	38
Horizontal and vertical	2	4
None	93	90
Total	135	138

Subjective Data

Following the experiment pilots were asked to assess the usefulness and desirability of the modified

traffic symbols and to describe how they used the TCAS display during the TA/RA sequence. All 23 expressed a preference for the modified symbology since they felt it improved their situation awareness and enabled a more rapid understanding of the potential threat posed by aircraft depicted on the traffic display.

Pilots were also asked to describe how they used the traffic display during the TA/RA sequence. In general, pilots indicated that prior to the RA they used the traffic display to anticipate required maneuvers and to assist in visual acquisition of traffic. Upon receipt of the RA, pilots indicated they directed attention to the primary flight display, and generally used the traffic display for quick glances to confirm vertical clearance from the intruder and/or to confirm that horizontal separation was increasing. This is consistent with the eye tracker results discussed earlier.

Discussion

This study was designed to determine the impact of traffic symbol directional information on pilot response to TCAS TA/RA events. This work is critical to the development of CDTI standards for shared TCAS/CDTI displays. The results of this study indicate that the presentation of traffic directionality information on a traffic display during a TCAS TA/RA sequence does not have a negative impact on pilot response to TCAS RAs, and subjective comments show that all of the pilots in this study preferred the modified traffic symbols. Independent of symbology, the relative pilot maneuvers prior to the RA was an interesting outcome. Each of these areas will be discussed below.

The eye-tracking data clearly show that the pilot flying the aircraft refers to the TCAS traffic display throughout the entire TCAS TA/RA sequence. During the TA portion of the TA/RA sequence, pilots devote almost half of their visual attention to the traffic display. Subjective comments indicate that the traffic display is used during the TA phase to anticipate maneuvers and visually acquire traffic. Once an RA is received, the data indicate that visual attention is devoted primarily to the PFD where RA guidance is depicted. The secondary focus of visual attention is directed to the traffic on the ND as indicated by the 10% proportion of gaze fixations

during the RA sequence. Subjective comments suggest that the primary function of these gazes is to ensure vertical separation from the traffic and to monitor horizontal separation. These analyses confirm the importance of the traffic display throughout the TCAS TA/RA sequence.

Given the relatively low amount of visual attention devoted to the traffic display following occurrence of the RA, it is not surprising that the modified traffic symbology did not affect pilot performance throughout the RA. The data indicate that neither the timing nor magnitude of pilot response to the RA was affected by the modified traffic symbology. The RA compliance rate observed in this study exceeded 95% for both the standard and modified symbology. This compliance exceeds that seen in other TCAS studies, which often show noncompliance rates of approximately 20 to 40% for TCAS Climb and Descend RAs [7]. The high degree of compliance noted in this study may be attributed to the simulator environment or to the inability of the pilot to visually acquire the intruder in many of the RA encounters. In actual operations, the FAA allows pilots to disregard the RA if they have definitive acquisition of the intruder and feel that safe separation can be maintained.

Although pilot maneuvering was not the focus of this study, the results indicate pilots did maneuver in response to the TA. While traffic symbology did not affect the rate of pilot maneuvering prior to the RA, the overall frequency of observed maneuvering merits further investigation. FAA guidance clearly states that pilots should not maneuver based solely on the traffic display [1]. However, some maneuvering was observed in one third of all encounters, and eye-tracking data suggests that the maneuvering decisions may have been influenced by traffic display information. Furthermore, while participants were instructed to follow existing FAA and company procedures, comments during the debriefing indicated that in many cases the maneuvering was initiated to avoid the issuance of an RA. In fact, some pilots indicated they maneuvered less frequently during this study than they would have during line operations.

Most of this maneuvering was in the form of reducing an existing climb or descent rate. These results are consistent with a previous simulator study which also found some vertical maneuvering in

response to TCAS TAs with the intention of avoiding an RA [2]. To the extent that this maneuvering does not result in a clearance deviation, it may represent an appropriate response. For example, the maneuvering may be seen by pilots as an extension of the guidance that recommends reducing vertical rate when leveling off below or above nearby traffic to avoid inducing a “nuisance” RA (an RA that functions as designed, but is inappropriate for the specific context).

Nevertheless, some clearance deviations occurred. First, in three of nine cases of vertical maneuvering while level, pilots deviated from their assigned altitude by more than 300 feet, with one deviation exceeding 1,000 feet. Additionally, in one of the cases of horizontal maneuvering, the pilot induced a second RA by turning rapidly back into the intruder once the pilot thought he was clear of the conflict. Since this study was not specifically designed to assess pilot maneuvering, a focused study may be appropriate to further assess the prevalence, magnitude and impact of pre-RA maneuvering on the air traffic system. This is especially relevant since a future collision avoidance system may incorporate horizontal as well as vertical resolution advisories.

Summary

In summary, this study indicates that inclusion of directionality in traffic symbology on a traffic display does not adversely affect pilot response to TCAS RAs. Pilots prefer the modified directional symbol presentation since it reduces the time and effort required to determine the relative direction of motion of potential intruders, particularly since the information can be obtained with a quick glance. This study also confirms that visual attention is frequently allocated to the traffic display during the TA in order to assist in visually acquiring traffic and to anticipate maneuvering. During the RA, less than one tenth of visual attention is directed to the traffic display and is reported by pilots in this study as intended to verify vertical clearance and horizontal separation from the intruder. Finally, the presence of directionality information does not appear to increase the likelihood of horizontal and vertical maneuvering prior to the RA. However, such maneuvering was often observed in this study. Further research is needed to better understand why, as well as the prevalence and impact that this maneuvering has on the air traffic system.

References

[1] FAA, 2001, Advisor Circular 120-55B Air Carrier Operational Approval and Use of TCAS II, Washington DC, Federal Aviation Administration.

[2] Chappell, Sheryl; Billings, Charles; Scott, Barry; Tuttell, Robert; Olsen, Christine; Kozon, Thomas, 1989, NASA Technical Memorandum 100094 Pilots' use of Traffic Alert and Collision Avoidance System (TCAS II) in Simulated Air Carrier Operations: Volume I: Methodology, Summary and Conclusions, Moffett Field, CA, National Aeronautics and Space Administration.

[3] Law, John, 2005, ACAS II Bulletin # 6 – Incorrect Use of the TCAS Traffic Display, EUROCONTROL Mode S and ACAS Programme.

[4] McAnulty, D. Michael and Carolina Zingale, 2005, DOT/FAA/CT-05/14 Pilot Based Spacing and Separation on Approach to Landing: The Effect on Air Traffic Controller Workload and Performance, Atlantic City, Federal Aviation Administration.

[5] Rantanen, Esa; Wickens, Chris; Xu, Xidong and Lisa Thomas, 2004, Developing and Validating Human Factors Certification Criteria for Cockpit Displays of Traffic Information Avionics, Champaign IL, University of Illinois.

[6] RTCA (2009). Minimum Operational Performance Standards (MOPS) for Aircraft Surveillance Applications System (ASAS). DO-317.

[7] Kuchar, James, Ann Drumm, 2007, The Traffic Alert and Collision Avoidance System, The Lincoln Laboratory Journal, 16 (2), pp. 277 – 296.

Acknowledgements

This paper was prepared by authors from Massachusetts Institute of Technology - Lincoln Laboratory, the FAA Technical Programs and Continued Airworthiness Branch (AIR-120), and the Behavioral Safety Research and Development Division at the Volpe National Transportation Systems Center. The Volpe Center contribution was completed with funding from the FAA Human Factors Research and Engineering Group (AJP-61). We acknowledge the support of Divya Chandra at Volpe who provided technical expertise and insightful comments on this paper and Robert

Marville who worked for CASE (Chenega Advanced Solutions & Engineering, LLC), and provided assistance with the eye tracking data analysis. We also thank the FAA Surveillance and Broadcast Services program office for their support.

The authors gratefully acknowledge the contributions of personnel from the FAA Flight Operations Simulation Branch (AFS-440) who provided extensive support in the development and design of the experiment. AFS-440 also provided the simulator facilities, simulator operators/observers, and pilots. Their support was truly outstanding. We also acknowledge the support of Shelly Lowe and Jerry Crutchfield of the FAA Office of Aerospace Medicine (AAM) - Civil Aerospace Medical Institute (CAMI) - Aerospace Human Factors Research Division (AAM-500), who provided support for the eye tracker used in this study. Finally, we also acknowledge the support and assistance provided by members of RTCA Special Committee 186, the Air Line Pilots Association (ALPA), and the professional pilots who participated in this study.

Disclaimer

The views expressed herein are those of the authors and do not necessarily reflect the views of the Volpe National Transportation Systems Center, the Research and Innovative Technology Administration, the Federal Aviation Administration, or the United States Department of Transportation.

The work conducted by MIT Lincoln Laboratory was performed under U.S. Air Force contract #FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are not necessarily endorsed by the U.S. Government.

Email Addresses

Wes.Olson@ll.mit.edu

Bill.Kaliardos@faa.gov

Michael.Zuschlag@dot.gov

Andrew.Kendra@dot.gov

*28th Digital Avionics Systems Conference
October 25-29, 2009*

Submitted for Publication to the 28th Digital Avionics Systems Conference October 25-29, 2009, Orlando, FL