HUMAN FACTORS STUDIES OF AN ADS-B BASED TRAFFIC ALERTING SYSTEM FOR GENERAL AVIATION

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Abstract

Mid-air collisions are a concern for general aviation. Current traffic alerting systems have limited usability in the airport environment where a majority of mid-air collisions occur. A Traffic Situation Awareness with Alerting Application (TSAA) has been developed which uses Automatic Dependent Surveillance – Broadcast (ADS-B), a Global Positioning System (GPS) based surveillance system, to provide reliable alerts in a condensed environment.

TSAA was designed to be compatible with general aviation operations. It was specifically designed to enhance traffic situation awareness and provide traffic alerting. The system does not include guidance or resolution advisories. In addition, the design was consistent with established standards, previous traffic alerting system precedents, as well as air traffic control precedent. Taking into account the potential financial burden associated with installation of a multi-function display (MFD), an audio based TSAA system was also designed to account for constrained cockpit space and the added cost of a MFD.

TSAA system performance and usability was tested by installing the system in an aircraft and having 21 general aviation pilots use the system in-flight. Pilots flew with the system during planned encounter testing as well as in typical high density traffic pattern environments in Daytona Beach, FL. Pilot's awareness of traffic awareness, out-the-window visual acquisition, and evasive action were recorded throughout the testing. A total of 109 encounters were analyzed comprising of 89 planned encounters and 20 targets of opportunity.

The alert provided the first indication of an encounter in a majority of cases. In general, pilots considered alerts to be appropriate in both the planned encounter cases and the targets of opportunity. In most cases, pilots did not deem evasive action necessary during the high density flights, despite considering the alerts to be appropriate.

Out-the-window visual acquisition was made in 40.5% of cases for the planned encounters, and 81.0% of cases for the targets of opportunity. For the cases where visual acquisition was made in the planned encounters, pilots made visual acquisition approximately 13s (SD=21s) after an alert annunciated. In target of opportunity cases, pilots made visual acquisition approximately 8 seconds (SD=32s) before an alert annunciated. The differences in visual acquisition could be due to the different geometries experienced with planned encounters as well as the different flight test regimes.

Pilots also indicated that the alert provided accurate information, and reported that they could trust the system. Pilots considered the alerts to be timely in 64% of encounters and too late in 36% of all encounters. In general subjective feedback suggested that the display symbology was effective, with some improvements desired in terms of font size and target vs obstacle discriminability. Overall the system was well received by pilots in the post-flight evaluation.

This research tested the pilot performance using the display system and the audio system. The findings of the studies will contribute to TSAA standards development for the FAA and design recommendations for avionics manufacturers. .

1 Introduction

A Traffic Situation Awareness with Alerting Application (TSAA) has been developed using the emerging ADS-B technology to reduce the occurrence of mid-air collisions. Effective human interaction is critical to the functionality and usability of the system in the cockpit.

1.1 Motivation

Mid-air collisions are a concern for general aviation (GA). Between 2004 and 2010, the mid-air collision rate involving general aviation aircraft averaged 10 per year. Approximately one-half of those collisions resulted in fatalities [1]. An MIT study analyzed 112 NTSB mid-air collisions involving general aviation aircraft between 2001 and 2010. Analysis indicated that 59% of collisions occurred in the airport environment [2]. There is a gap between the capabilities of current traffic alerting systems and the environment where most collisions occur.

1.2 Current State-of-the-Art Traffic Systems

Traffic alerting systems have been developed for general aviation aircraft such as Traffic Information Systems (TIS) and Traffic Advisory Systems (TAS). TIS is a ground-based service that transmits radar data to aircraft equipped with a Mode S transponder. The TIS service uplinks information on radar traffic to the aircraft, and the position and trend information is presented to the pilots on a dedicated display or a multi-function display (MFD). TIS is limited to radar coverage and radar update rates so the information provided by TIS only updates every 4-12 seconds.

TAS actively interrogates aircraft in a given proximity through transponder range interrogation, displays the location and trend information on a MFD, and provides aural alerts to help pilots locate conflicting traffic.

Traffic Collision Avoidance System II (TCAS II) is a system primarily used in commercial aviation where flight crews receive both traffic alerts and resolution advisories, which provide guidance on the evasive maneuver required.

Neither TAS, TIS, nor TCAS I, are designed to provide resolution guidance. Though all existing systems contribute to traffic situation awareness in the cockpit, because of the quality of the surveillance and the challenging environment, it is difficult for TAS, TIS, and TCAS, to operate in close proximity to other aircraft and alert reliably on maneuvering targets; therefore, these systems are often less effective in the airport environment.

1.3 Traffic Situation Awareness with Alerting Application (TSAA)

Using the enhanced information provided by Automatic Dependent Surveillance –Broadcast (ADS-B), a Traffic Situation Awareness with Alerting Application (TSAA) was developed with the purpose of providing reliable prediction capabilities in the general aviation environment. ADS-B offers the potential for more reliable alerting in a dynamic airport environment by providing more precision than radar and a faster update rate (1 second) [3]. When augmented by ADS-R, ADS-B is not limited by horizontal line of sight reception between aircraft. It can also be used at altitudes lower than traditional radar-based systems. Additionally, the enhanced update rate of ADS-B allows a prediction to be developed that better accounts for maneuvering flight, which is a capability the current state-of-the-art technology does not provide.

ADS-B Out has been mandated by the Federal Aviation Administration (FAA) in support of the Next Generation Air Transportation System (NextGen) implementation. Additionally, the benefits of TSAA may compel some users to install ADS-B equipment in their aircraft prior to the FAA mandate [4].

The three key elements of TSAA are ADS-B surveillance, alerting logic, and human interface. The focus of this research was the design of the interface and human interaction with the system. The goal of this research is to develop an interface for the TSAA system and evaluate the TSAA interface through a series of simulations and flight testing involving general aviation pilots. The final step of development included testing the system in an operational environment, and the results of flight testing are presented in this document. Overall objectives for TSAA flight testing included demonstrating functionality of TSAA and addressing any operational issues which may arise during prototype development.

The specific objectives of human factors flight testing for TSAA included testing basic usability and functionality of the system in an operational environment with subjective feedback from general aviation pilots, evaluating pilot traffic awareness & response to alerts in an operational environment, and investigating subjective criteria for nuisance alerts. The outcomes of human factors testing provided feedback for algorithm tuning as well as provided feedback to decision-makers regarding the pilot acceptability and usability of the system.

2 System Design

2.1 Design Philosophy

TSAA was designed to be compatible with general aviation operations. It was specifically designed to enhance situation awareness and provide traffic alerting. The system does not include guidance or resolution advisories. In addition, the design was consistent with established standards, previous traffic alerting system precedents, as well as air traffic control precedent. Taking into account the potential financial burden associated with installation of a multi-function display, an audio based TSAA system was also designed to account for constrained cockpit space, added cost and added weight of a Multi-Function Display (MFD).

2.2 TSAA Alerting Criteria

The alerting system inputs information from ownship and target surveillance to determine whether a collision threat exists between ownship and other aircraft. The system inputs ADS-B position and velocity and propagates the trajectory of each aircraft within range of the ownship. Two airspace zones were defined to characterize the threat level of an aircraft. As can be seen in Fig 1, two cylinders are calculated around a target aircraft. The

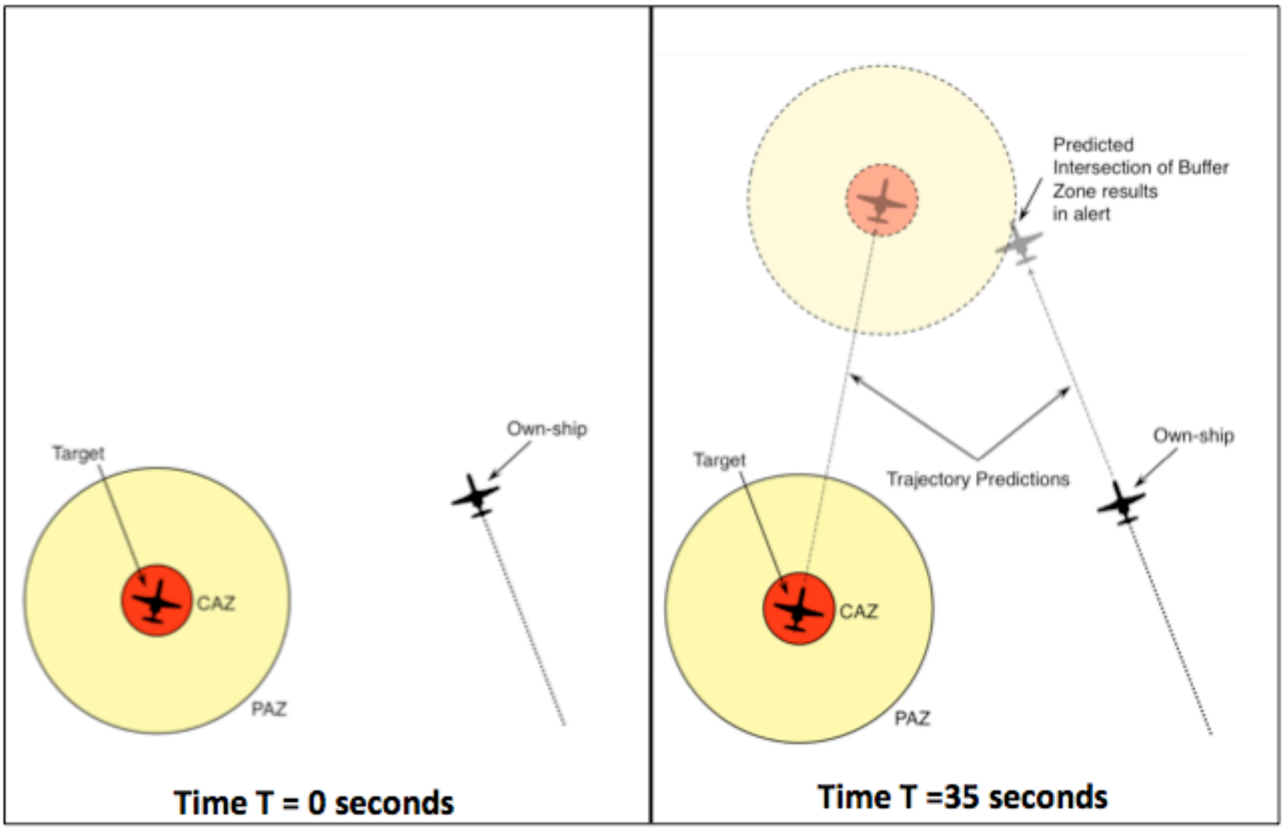

Fig 1. Sample conflict describing alerting criteria

protected airspace zone (PAZ) is a variable sized cylinder surrounding the target aircraft (depicted in yellow in Fig. 1). The size of the PAZ is scaled based on the closure rate of the traffic; when a threat has a high closure rate, the PAZ increases in size and when the threat has a low closure rate, the PAZ shrinks. The minimum size of the PAZ is 750 feet in radius, and +/- 450 feet in altitude, so that it is always larger than the Collision Airspace Zone (CAZ). The CAZ is a fixed size cylinder around the target (depicted in red in Fig. 1). The radius of the CAZ is 500 feet and the altitude spans +/- 200 feet.

The system propagates target and ownship position 35 seconds into the future as is shown on the right side of Fig. 1. If at any point in that time period, the ownship penetrates either the CAZ or PAZ, an alert is issued. If penetration of the PAZ is predicted, a Traffic Caution Alert is annunciated. If penetration of the CAZ is predicted, a Traffic Caution Alert is re-annunciated with updated information.

ADS-B data is subject to various inherent errors in position, velocity, update rate, and latency. These could originate from GPS error or processing time delays. In addition to ADS-B targets, the TSAA system processes information from radar targets. These targets' data is subject to the type of radar as well as the information update rate. The TSAA system is designed to perform using a minimum data quality, however there is the possibility where data quality is so poor, a reliable alert cannot be provided.

2.3 TSAA Human Interface

Through a series of design reviews with FAA and industry reviewers, potential human factors concerns were identified. Reviewers consisted of members from the FAA ADS-B Program Office, FAA Aircraft Certification, FAA Flight Standards Service, FAA Human Factors Division, Department of Transportation Volpe Center, and the Avidyne Corporation. The baseline design was refined through a series of eight design reviews, and the residual issues identified were probed through a series of three human factors simulations where pilots were presented with traffic encounter scenarios and expected to respond to traffic [5]. The interface used during flight testing was the recommended design based on these simulations and expert review.

The TSAA interface consists of an audio component and a visual component.

2.3.1 Audio Interface

The audio interface is present in both the audio based and display based TSAA systems. The aural alerts are annunciated for the Traffic Caution Alert and includes azimuth, range, relative altitude, and vertical trend information (e.g. "Traffic, 3 o'clock, high, 2 miles, descending").

2.3.2 Display Interface

The TSAA display based system includes a CDTI. An example of the symbology displayed on a CDTI is shown in Fig. 2.

Display symbology for the TSAA system was based on FAA standards for traffic with ADS-B information [6]. Data tags for TSAA include relative altitude in hundreds of feet, vertical trend information, call sign, and data quality (if applicable). Any instance where altitude, vertical trend, and call sign are valid, they are displayed on the data tag.

The Traffic Caution Alert for directional targets is depicted using the yellow caution symbol. Non-directional targets which alerted were displayed using current TAS symbology (not depicted in figure), and were depicted as a filled yellow circle in the prototype.

No current guidance exists regarding display of alert traffic that is outside the current MFD range setting. In order to maintain consistency with previous TAS systems, off-scale alert traffic were depicted in TSAA by a half-symbol on the compass rose located at the relative bearing to traffic (not depicted in figure).

3 Flight Test Design

Because TSAA was designed to provide reliable alerting in a typical general aviation environment, it was necessary to assess usability and functionality of the system in an actual flight environment. Considering a major

Fig. 2. Sample scenario with TSAA symbology on MFD map background

limitation of the current state of the art traffic alerting systems (TIS, TAS, and TCAS) is perceived nuisance alerting in the traffic pattern, it was important to gauge pilot perception of TSAA nuisance alerting in the airport environment.

In order to evaluate the TSAA system in a representative environment, two types of flights were conducted. Planned encounter flights were used to expose pilots to a variety of encounter scenarios; high density flights were used to expose pilots to use of the system in typical enroute and traffic pattern environments using targets of opportunity.

3.1 Planned Encounter Flights

Planned encounter flights were conducted to expose pilots to a variety of enroute and pattern encounter scenarios, which were representative of historical accidents or tested the performance limits of the system. Pilots actively controlled the ownship and were presented with flight profiles to fly. A coordinated intruder aircraft then forced pre-planned encounters with the ownship to a predefined minimum separation at which an encounter was broken off. Following each encounter, a post-event questionnaire was presented to the subject pilot verbally. Once the flight was complete, subject pilots were presented with an online post-evaluation questionnaire regarding their overall perception of the system.

The subset of encounters were chosen to 1) test the system in a variety of closure speeds and geometries, and 2) test human performance in more “difficult” cases identified by the previously conducted simulator testing of TSAA. The 5 encounters that pilots experienced during planned encounter testing are listed below.

1. Horizontal Low Closure Overtake
2. Vertical High Closure Rate
3. Head On
4. Overtaking on Final
5. Entry vs. Downwind

3.2 High Density Flights

In order to test TSAA in a challenging environment, testing was conducted in a high density general aviation traffic pattern. Daytona Beach, FL (KDAB) was used as the high density pattern due to the high number of training flights conducted at the airport.

Each flight departed out of Melbourne, FL (KMLB). Subjects flew to KDAB, spent approximately 30 minutes in the KDAB traffic pattern and then returned to KMLB. Following each alert scenario with a target of opportunity, control was handed to the safety pilot, and a post-event interview was conducted. Upon landing, a post-flight evaluation was conducted.

4 Test Equipment and Experimental Protocol

4.1 Aircraft and Personnel

The ownship used was a Cessna 182 aircraft with conventional instruments and an EX600 MFD. All aural alerts were annunciated through the headsets as well as through the aircraft speakers. The intruder aircraft was a Cirrus SR22.

There were four occupants in the ownship. A visualization of the ownship personnel is presented in Figure 4-4 viewing the aircraft from the rear looking forward. The subject pilot flew the aircraft from the left seat. A safety pilot served as pilot in command from the right seat of the aircraft.

Two human factors specialists sat in the back seats. Human Factors (HF) Specialist 1 was in charge of collecting verbal data as well as conducting the post-event questionnaire. HF Specialist 2 held test conductor responsibilities.

4.2 Dependent Variables

Data was being recorded by voice recorders, TSAA equipment, video recorders, and manually using a laptop. The time of awareness was taken by the first awareness the subject had regarding the impending encounter (via the display, out-the-window visual acquisition, or alert). The time of visual acquisition was taken by the initiation of the "traffic" call when participants stated "traffic in sight." The time of visual acquisition was only used when subjects acquired traffic without test conductor or safety pilot point out. The time of evasive response was determined as the time the pilot verbalized that he would take evasive action.

Subjective evaluations were also collected from the participants. Background questionnaires were completed prior to data collection and consisted of questions regarding pilot experience, access to aircraft, and experience with traffic alerting systems.

A post-event questionnaire was used to collect data regarding perception of the system for each encounter. This questionnaire probed perception of appropriateness of the alert, timeliness, accuracy, as well as whether the pilot would have taken evasive action and what action would have been taken.

The post-evaluation questionnaire was conducted at the end of the experiment probing general usability, clutter, display issues, perception of the best and worst features of the TSAA system, trust, as well as perceived value of the system. The questionnaire was presented to subjects on a computer.

Fig. 3. Flight test personnel

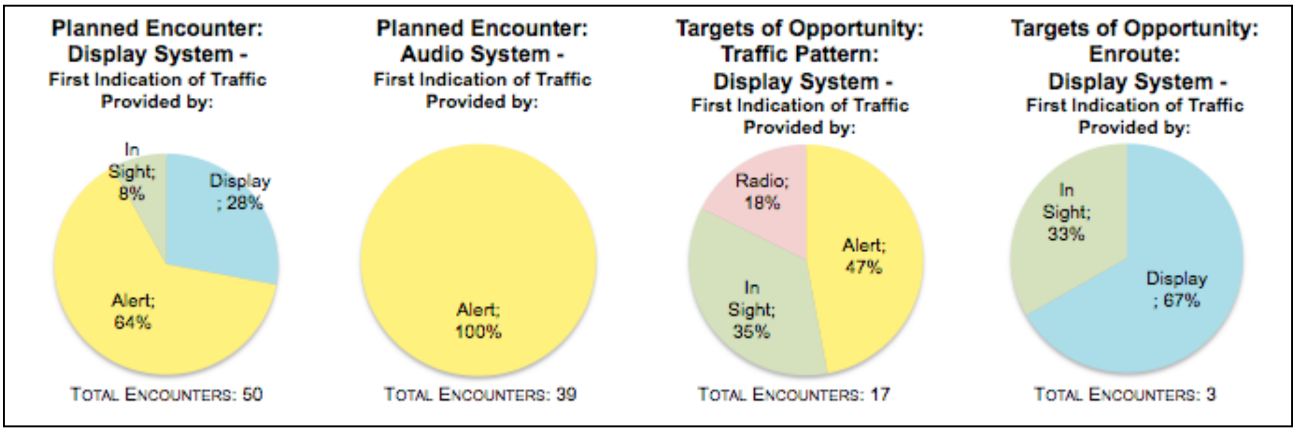

Fig. 4. First indication of traffic encounter

5 System Performance

A total of 109 usable encounters remained for analysis. 89 of these were planned encounter (50 display-system, 39 audio-system), and 20 encounters involved targets of opportunity (17 in traffic pattern, 3 enroute).

Twenty one general aviation pilots experienced the TSAA system. Thirteen participants flew with the display based system, while eight participants flew with the audio based system. Pilots were chosen to reflect a range of experience levels as well as a range of experience types from recreational to professional.

5.1 Inflight Performance and Subjective Response

5.1.1 First Indication of Encounter

The results for the first indication of encounter are presented in Fig. 4 for the planned encounter environment (display and audio systems) as well as the targets of opportunity, both enroute and in the pattern.

Overall, the alert provided the first indication of an encounter in a majority of cases. In the audio system, the alert provided the first indication in all of the 39 encounters. For encounters with targets of opportunity in the traffic pattern, a higher percentage of encounters were first identified visually. This is expected due to the primarily visual flight regime of the traffic pattern. Also in the pattern, pilots did receive information about traffic from radio communications. Note that radio communication was not given to pilots as a resource during the planned encounter testing.

5.1.2 Planned Encounter Flights

Pilots were probed regarding their perception of whether a given alert was appropriate or nuisance in the post-event interview following each encounter. For the planned encounters, shown in Fig. 5, pilots considered the alerts to be appropriate in 91.7% of cases for the display system and 94.6% of cases for the audio system. In all 6 cases where pilots considered the alert a nuisance, the target was never visually acquired.

	Display Based System		Audio Based System	
Scenario	Appropriate	Nuisance	Appropriate	Nuisance
LCR Overtake	16	0	12	1
High VCR	8	1	5	1
Head On	7	0	7	0
Overtaking Final	5	2	6	0
Entry vs. Downwind	8	1	5	0
Total Percentage	91.7%	8.3%	94.6%	5.4%

Fig. 5. Perception of nuisance alerts for the planned encounter environment

Pilots rated timeliness of the alert during the post-event questionnaire. They rated the alert as too early, timely, or too late. Overall, pilots tended to perceive the alerts as timely or too late with no cases of the alert being too early. The timeliness results for planned encounters is presented in Fig. 6. In the display based system, pilots considered the alerts to be timely in 53.1% of cases and too late in 46.9% of cases. In the audio system, pilots considered the alerts as timely in 73.5% of cases and late in 26.5% of cases.

	Display Based System			Audio Based System		
Scenario	Too Early	Timely	Too Late	Too Early	Timely	Too Late
LCR Overtake	0	8	8	0	7	4
High VCR	0	4	5	0	4	1
Head On	0	5	2	0	6	1
Overtaking Final	0	5	2	0	5	1
Entry vs. Downwind	0	4	6	0	3	2
Total Percentage	**0.0%**	**53.1%**	**46.9%**	**0.0%**	**73.5%**	**26.5%**

Fig. 7. Perception of timeliness of alerts for the planned encounter environment

Pilots rated accuracy of the alert during the post-event questionnaire. Pilots were asked whether they considered the location (clock position) and distance of the traffic called out in the aural alert to be accurate or inaccurate. In the case that the subjects considered the information inaccurate, they were probed about why they considered it inaccurate. Fig. 7 shows the perceived accuracy of alerts during the planned encounter flights. Overall, accuracy was rated as good when the traffic was visually acquired. In the display system, pilots rated the position and distance as accurate in 83.3% of cases where visual acquisition was made. In the audio system, pilots rated the information as accurate in 88.9% of cases. The inaccurate cases for both the display and audio cases were dependent on when the pilot made visual acquisition with the target. In 4 out of the 6 inaccurate cases, pilots reported that the target looked closer than what was reported in the alert. In another inaccurate case, the pilot reported that he found the target closer to 12 o'clock when the alert annunciated 11 o'clock. The final inaccurate case was due to the pilot observing the target on the breakaway maneuver following the encounter.

	Display Based System			Audio Based System		
Scenario	Not Acquired	Inaccurate	Accurate	Not Acquired	Inaccurate	Accurate
LCR Overtake	11	1	4	9	0	5
High VCR	4	2	3	4	0	2
Head On	0	1	6	1	2	2
Overtaking Final	7	0	1	4	0	3
Entry vs. Downwind	4	0	6	1	0	4
Total Percentage	**52.0%**	**8.0%**	**40.0%**	**51.4%**	**5.4%**	**43.2%**
If Acquired Percentage		**16.7%**	**83.3%**		**11.1%**	**88.9%**

Fig. 6. Perception of accuracy for planned encounter environment

5.1.3 High Density Flights

As is seen in Fig. 8, in 80% of cases, pilots considered the alerts on targets of opportunity to be valid. There were four alerts that were considered as nuisance alerts by the participants. The overtake case was considered nuisance because it occurred on short final. The "other pattern" case was an alert on traffic entering downwind while the ownship was turning crosswind, and was considered nuisance because the pilot had visually acquired the traffic prior to the alert. The 2 turning alerts that were considered nuisance occurred during a time that the display experienced difficulty. Alerts for two separate aircraft were received during this time, and the evaluation of the alerts as nuisance may have been influenced by the hardware problem.

		Display Based System	
	Scenario	Appropriate	Nuisance
PATTERN	Turning Alerts	9	2*
	Parallel Runway Alerts	3	0
	Overtakes	1	1
	Other Pattern	0	1
	Enroute	3	0
	Total Percentage	**80%**	**20%**

Fig. 8. Perception of nuisance alerts for the targets of opportunity (*the two nuisance turning alerts during a display anomaly)

The timeliness results for the targets of opportunity is presented in Fig. 9. In the display based system, pilots considered the alerts to be timely in 76.5% of cases and too late in 23.5% of cases. During all of the reported cases, the system was functioning as designed.

		Display Based System		
	Scenario	Too Early	Timely	Too Late
PATTERN	Turning Alerts	0	7	2
	Parallel Runway Alerts	0	2	1
	Overtakes	0	1	0
	Other Pattern	0	1	0
	Enroute	0	2	1
	Total Percentage	**0.0%**	**76.5%**	**23.5%**

Fig. 9. Perception of timeliness of alerts for the targets of opportunity

Pilots again rated accuracy of the alert during the post-event questionnaire during the high density flights. Pilots were asked whether they considered the location (clock position) and distance of the traffic called out in the aural alert to be accurate or inaccurate. In the case that the subjects considered the information inaccurate, they were probed about why they considered it inaccurate. Fig. 10 shows the perceived accuracy of alerts during the target of opportunity flights. Again, accuracy was rated as good when the traffic was visually acquired. Pilots rated the position and distance as accurate in 84.2% of cases where visual acquisition was made. The 3 cases where alert was rated inaccurate, the pilot rated it as such because he understood the “less than one mile” annunciation to indicate that the traffic was to the left. It is possible to consider other options to relay distance information such as "within one mile" or "inside one mile," however they were not tested in these studies. It may be prudent to study possible other options as further research.

Overall however, pilots considered the location and distance information provided in the alert to be accurate.

		Display Based System		
	Scenario	**Not Acquired**	**Inaccurate**	**Accurate**
PATTERN	Turning Alerts	0	2	9
	Parallel Runway Alerts	0	0	3
	Overtakes	0	0	1
	Other Pattern	0	1	0
	Enroute	0	0	3
	Total Percentage	**0.0%**	**15.8%**	**84.2%**
	If Acquired Percentage		**15.8%**	**84.2%**

Fig. 10. Perception of accuracy of alerts for the targets of opportunity

5.2 General Post-flight Subjective Feedback

Subjectively, the system was well received by the pilots in the post-flight evaluation, and trust was rated highly. Non-displayed aircraft and dropouts of targets on and off the display negatively influenced perception of the system. In general, the number of alerts were considered appropriate and aural alerts were rated as easy to understand. Pilots in general preferred more constant updates on an encounter. The mute functionality and call sign information were not widely used by pilots, however the repeat functionality in the audio system was valued by some pilots. Pilots were generally accepting of the system and did not indicate major interference of the system with normal pilot operations or radio communications.

6 Summary and Conclusions

A Traffic Situation Awareness with Alerting Application (TSAA) was developed which uses ADS-B, a GPS based surveillance system, to provide reliable alerts in a condensed environment.

TSAA system performance and usability was tested by installing the system in an aircraft and having 21 general aviation pilots use the system in-flight. Pilots flew with the system during planned encounter testing as well as in typical high density traffic pattern environments in Daytona Beach, FL. Pilot’s awareness of traffic, visual acquisition, and evasive action were recorded throughout the testing. A total of 109 encounters were analyzed comprising of 89 planned encounters and 20 targets of opportunity.

Overall, the system alerted as expected. The alert provided the first indication of an encounter in a majority of cases. In general, pilots considered alerts to be appropriate in both the planned encounter cases and the targets of opportunity. In most cases, pilots did not deem evasive action necessary during high density flights, despite considering the alerts to be appropriate.

Visual acquisition was made in 40.5% of cases for the planned encounters, and 81.0% of cases for the targets of opportunity. For the cases where visual acquisition was made in the planned encounters, pilots tended to make visual acquisition approximately 13 seconds (SD=21s) after an alert annunciated. In target of opportunity cases, pilots made visual acquisition approximately 8 seconds (SD=32s) before an alert annunciated. The differences in visual acquisition could be due to the different geometries encountered with planned encounters as well as the different flight regimes.

Pilots also indicated that the alert provided accurate information, and reported that they could trust the system. Pilots considered the alerts to be timely in 64% of encounters and too late in 36% of all encounters. In general subjective feedback suggested that the display symbology was effective, with some improvements desired in terms of font size and target vs obstacle discriminability. Overall the system was well received by the pilots in the post-flight evaluation.

This research tested the pilot performance using the display system and the audio system. The findings of the studies will contribute to TSAA standards development for the FAA and design recommendations for avionics manufacturers.

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