AIAA Aviation Forum and ASCEND co-located Conference Proceedings
29 July - 2 August 2024, Las Vegas, Nevada
AIAA AVIATION FORUM AND ASCEND 2024

10.2514/6.2024-4540

Helicopter Pilot Evaluations of the Airborne Collision Avoidance System Xr in a High-Fidelity Motion Simulation

Casey L. Smith* and R. Conrad Rorie*
NASA Ames Research Center, Moffett Field, CA, 94035, USA

New aircraft and aerial Urban Air Mobility operations require updated technologies to maintain vehicle separation during flight. Specifically, higher-density airspace will need more than traditional air traffic control to keep vehicles well clear of each other and avoid Near Midair Collisions. In response, the Federal Aviation Administration is currently developing the Airborne Collision Avoidance System X (ACAS X) for next-generation air traffic deconfliction, which provides caution-level and warning-level alerts in response to multiple aircraft types. This study recruited six helicopter pilots to fly an electric vertical takeoff and landing vehicle model in simulated operations under Visual Flight Rules (VFR). Flights were accomplished using the high-fidelity Vertical Motion Simulator at the NASA Ames Research Center. Participants controlled the vehicle using two side inceptors and foot rudders. The rotorcraft variant of ACAS X (ACAS Xr) was provided for alerting and guidance during traffic conflicts. Pilots used this system while giving feedback to the researchers through questionnaires, debriefs, and other discussions. Variables of interest to the study were phases of flight (i.e., Cruise, Hover, and Approach) and ACAS Xr configurations: The Collision Avoidance System configuration behaves similarly to current commercial traffic systems used for tactical deconfliction in crewed vehicles, and the Detect and Avoid configuration was developed to provide extra, corrective-level guidance for unmanned aircraft systems. Results showed that pilots found the alerting and guidance from ACAS Xr useful, effective, and acceptable for VFR operations. Certain elements, like speed guidance and text banners, were found to be of no use to the pilots. Hover and Approach scenarios were considered the most difficult for ACAS Xr alerting. Reasons for this difficulty were partially due to learning interference (i.e., overcoming previously learned behavior) and partially due to the vehicle model (i.e., NASA's Lift Plus Cruise design). Still, alerting-based confounds reveal the need for more development for ACAS Xr during these Hover and Approach flight phases. Study caveats and future projects are discussed.

I. Introduction

Urban Air Mobility (UAM) is a potentially transformative concept in aviation that seeks to address the increasing demands for efficient and sustainable airborne urban transportation. As cities explore the potential benefits of UAM, such as reduced ground-based traffic congestion and faster commuting, revolutionary approaches to airspace and vehicles are being proposed by industry. Firstly, innovative models of unmanned aircraft systems (UAS) and crewed rotorcraft, with a diversity of airframes, propulsion systems, energy sources, vertical takeoff and landing (VTOL) styles, and flight control schemes have inundated the aviation market [1]. These new types of highly automated aircraft will introduce 'simplified vehicle operations'; these operations will include new types of training and certification for pilots and remote operators that are quicker, less expensive, and more vehicle-specific than comparable contemporary flight licensure [2]. Additionally, the integration of these vehicles in densely populated areas necessitates comprehensive safety measures; an example of these measures is a Provider of Services for UAM (PSU) that can

* Research AST, Human Systems Integration Division, MS262-2.

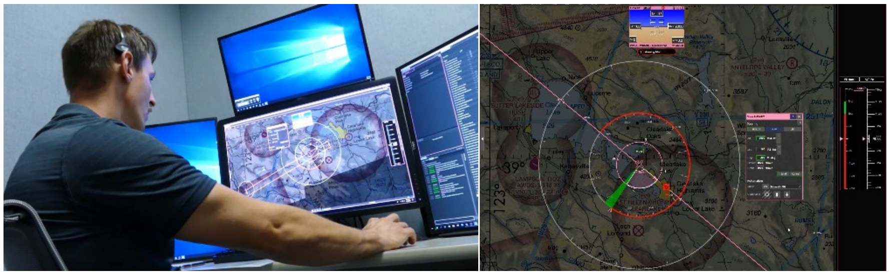
supplement crewed Air Traffic Control (ATC) efforts by providing UAM operators immediate and automated services like airspace advisories, weather information, and strategic traffic deconfliction [3].

A crucial aspect of enabling safe UAM operations involves reimagining the traditional 'see and avoid' (SAA) method of aircraft separation, which involves onboard pilots visually monitoring other aircraft during flight [4]. Consequently, there is a growing focus on developing and implementing robust and reliable Detect and Avoid (DAA) systems, introduced initially to UAS to ensure the safe coexistence of these aerial vehicles with existing infrastructure [5]. These DAA systems are essential for enhancing situational awareness and avoiding conflicts in shared airspace; the systems do so by utilizing advanced, multi-sensor packages to detect nearby aircraft and potential collision risks. Research in collision avoidance systems explores sensor fusion techniques, machine learning algorithms, and real-time communication protocols to optimize the accuracy and responsiveness of DAA systems, contributing to the overall safety of UAM [6].

The Traffic alert and Collision Avoidance System (TCAS II) has played a pivotal role in providing a collision avoidance (CA) capability for traditional aircraft. TCAS II is designed to prevent near-midair collisions (NMACs) by providing pilots with timely Resolution Advisories (RAs). Pilots receive these RAs as a combination of visual and aural indicators during conflicts. Even though TCAS II has proven effective in conventional airspace, adapting this system to the more dynamic and crowded environments of UAM presents unique challenges [7]. Therefore, researchers and developers continue to explore tactical deconfliction technologies that can accommodate the intricacies of low-altitude urban flight, such as rapid changes in direction, varying altitudes, and the integration of new autonomous and piloted vehicles.

Understanding and anticipating this evolving UAM landscape has led to the ongoing development of traffic monitoring systems such as the Airborne Collision Avoidance System X (ACAS X) [8]. ACAS X logic can be tuned to commercial aircraft, large UAS, small UAS, and rotorcraft by equipping them with ACAS Xa, Xu, sXu, and Xr, respectively [9]. ACAS Xr is designed to provide DAA and CA capabilities in response to transponding and non-transponding airborne traffic. DAA alerting and guidance are both currently caution-level and suggestive. These indicators are provided to pilots to assist in situational awareness and decision making should maneuvers be necessary to maintain predefined DAA "well-clear" separation volumes, which vary according to where the aircraft are operating (e.g., en-route, terminal area, structured/dense airspace) [10]. At the time of the study, ACAS Xr allowed for DAA alerting and guidance in the horizontal (i.e., right turns and left turns), vertical (i.e., climbs and descends), and speed (i.e., accelerate and decelerate) dimensions. Alerting for CA is warning-level and "directive." These directives oblige pilots to maneuver in prescribed directions to prevent NMACs, which are defined as an incursion into a volume of space 500 feet horizontally and 100 feet vertically around the ownship aircraft. Similar to TCAS II, these warning-level alerts are offered as RAs. However, ACAS's RAs may command a target heading (Horizontal RA), target vertical speed (Vertical RA), or both at once (Blended RA). Some RAs instruct pilots to discontinue maneuvers. RAs provided to stop turns are referred to as Maintain Heading RAs, and those provided to cease altitude changes are referred to as Level Off RAs. Both caution-level and warning-level alerts are offered both visually (using icon changes and banding) and audibly (using aural cues) [11].

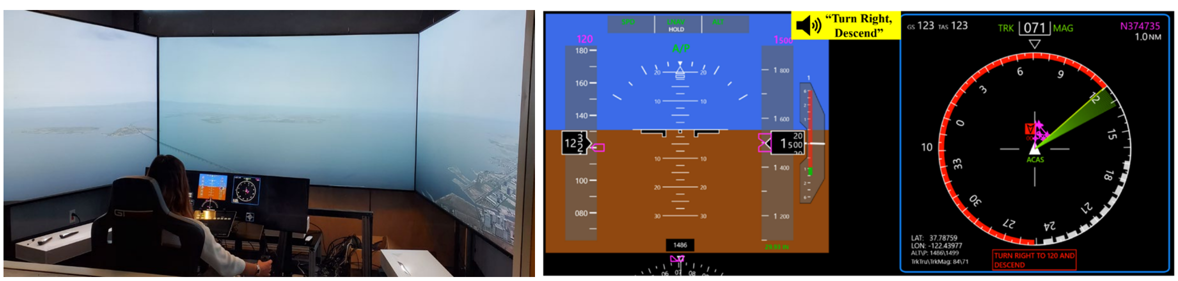
Previous human-in-the-loop (HITL) simulations with UAS explored different tactical deconfliction systems and ways of presenting DAA and CA alerting and guidance. In one study, remote pilots were recruited and tasked to maintain separation from simulated air traffic using ACAS Xu in a ground control station (Fig. 1). An analysis showed that the combination of DAA and RA alerting and guidance helped pilots reduce the severity of loss of well-clear during scripted traffic conflicts [12]. During this time, pilots declared that the assistance provided by ACAS Xu was reasonable and effective. However, the pilots also voiced that Horizontal RAs, and the subsequent updates made to the target heading, were too frequent. These excessive updates could lead to less trust in the system overall and a tendency to disregard Horizontal RAs [13].



(a) (b)

Fig. 1 Uncrewed, ground control station configuration for ACAS Xu study: (a) Remote pilot operating UAS with a mouse and keyboard, (b) Map display depicts a traffic conflict and an ACAS Xu Blended RA.

A previous HITL study with ACAS Xr introduced the concept of DAA alerting and guidance in a crewed electric VTOL (eVTOL) configuration. The researchers recruited helicopter pilots and tasked them with maintaining well-clear against simulated traffic in a fixed-based simulator (Fig. 2). Since this study was the initial examination of ACAS Xr, several real-world factors were not included, like ATC calls, background traffic, and out-of-window traffic, allowing pilots to focus solely on the alerting and guidance provided by the system. Results showed that ACAS Xr led to good performance with few instances of losses of DAA well-clear and NMACs. These results applied to the RA directives and DAA alerting and guidance. Pilots found that the DAA guidance was beneficial for situational awareness and that DAA response times were much faster compared to simulations with uncrewed configurations (i.e., ACAS Xu). Pilots were also observed making more vertical and multi-axis maneuvers against the suggestive DAA guidance than remote operators using ACAS Xu in previous uncrewed simulations, who were much more likely to maneuver the UAS laterally. Pilots did, however, report that ACAS Xr over-relied on horizontal RA guidance. Pilots also noted that a lack of terrain and obstacle awareness led to a distrust of the system; this distrust caused pilots to override RAs that directed the aircraft too close to the ground [14]. While terrain and obstacle awareness can be incorporated into the ACAS Xr logic, this prior study could not leverage that feature.



(a) (b)

Fig. 2 Crewed cockpit configuration for former ACAS Xr study: (a) Pilot flying vehicle using an inceptor, (b) The ACAS Xr traffic display and Primary Flight Display (PFD) depicts a Blended RA.

The present study was a HITL simulation that also examined the use of ACAS Xr in a crewed eVTOL vehicle configuration. Flights were conducted in a full-motion, high-fidelity simulation platform at the NASA Ames Research Center (ARC) in Moffett Field, California, USA. The simulation allowed helicopter pilots to explore the two Xr configurations (i.e., Collision Avoidance System [CAS] and Detect and Avoid [DAA]) to respond to air traffic conflicts while experiencing motion. The simulator also allowed pilots to assess these Xr conditions in three phases of flight: Cruise, Hover, and Approach. Figures 3a and 3b show examples of the cockpit design and ACAS Xr traffic display for the current study, and further details are provided in the following sections. This study was approved by the NASA Institutional Review Board and was performed in support of NASA's Advanced Air Mobility (AAM) project under the Automated Flight and Contingency Management (AFCM) sub-project.

(a) (b)

Fig. 3 Crewed cockpit configuration for current ACAS Xr study: (a) Pilot flying vehicle using inceptors, (b) The ACAS Xr traffic display depicts a Blended RA.

II. Method

A. Participants

Researchers recruited six pilots, each with a private helicopter pilot license. All pilots were male, with an average age of 51 (*SE* = 4) years. Pilots reported an average of 4,542 (*SE* = 1275) hours of rotorcraft flight. Of the six pilots, five had an average of 820 (*SE* = 552) hours of fixed-wing flight, four declared they were familiar with TCAS II, four had military training, five had nap-of-the-earth (i.e., very low and terrain-tracing) flight experience, and all were IFR rated on helicopters, fixed-wing aircraft, or both.

B. Vehicle Models

The vehicle modeled in this simulation was NASA's Lift Plus Cruise (NLPC) hybrid eVTOL design (Fig. 4). This concept aircraft can fully transition from thrust-borne lift to wing-borne flight, using eight wing-mounted lifting thrusters and one rear-mounted push propeller. The flight characteristics of the model progress as thrust-borne below 20 knots true airspeed (KTAS), semi-thrust-borne at 20-60 KTAS, semi-wing-borne at 40-90 KTAS, and full-wing-borne at 100 KTAS or more. During the project, the model was being developed at ARC [15]. This concept was used for both the ownship and intruder aircraft, and the vehicles were configured for a maximum cruise speed of 110 KTAS, flight altitude of 1500 feet mean sea level (MSL), maximum bank of 40 degrees, and climb/descend rate of 1000 feet per minute.

Fig. 4 NASA's Lift Plus Cruise Vehicle model.

C. Simulation Environment

This HITL project occurred at the ARC's Vertical Motion Simulator (VMS). As the name suggests, the VMS is a motion-based platform that produces six degrees of movement: roll, pitch, yaw, surge, sway, & heave; together, these movements can simulate acceleration forces, turbulence, and other types of tactile feedback experienced in flight. The VMS also provides high-fidelity displays and out-the-window graphics that include elements like terrain, manmade structures, and traffic [16]. This simulator was configured for the ownship and intruder aircraft to fly in Class E airspace in the San Francisco Bay Area under Visual Flight Rules (VFR). Both aircraft began encounters at mission altitude and on pre-recorded courses, designed so that both aircraft were scripted to cross flight paths. The ownship was initialized with the autopilot engaged, flying waypoint-to-waypoint while maintaining preprogrammed tracks, speeds, and altitudes. The ownship encountered only the intruder aircraft during the scenario, and no additional background traffic, airspace-specific procedures (e.g., approach procedures for terminal environments), or ATC/PSU interactions were present. Upon completion of an encounter, the system was reset so that the ownship and intruder aircraft were repositioned for subsequent conflicts.

D. Displays and Controls

Pilots were situated in a rotorcraft cabin; this design mimicked an industry-inspired air-taxi cockpit, complete with three front-facing windshield monitors, two chin bubble monitors, and a custom instrument panel. The instrument panel contained the Map Display, Primary Flight Display (PFD), and Traffic (i.e., ACAS Xr) Display. Although some information was repeated across screens, each display offered pilots unique information. The Map display specialized in the ownship's geographic location, route, ranges, and maneuver data. The PFD showed the ownship's status, flight mode, and indicators that monitored the vehicle's pitch, yaw, roll, heading, speed, and altitude. Synthetic vision was offered for the backgrounds of the Map Display (top-down) and PFD (forward-facing). The Traffic Display showed aircraft near the ownship and alerting and guidance provided by ACAS Xr; this display offered the additional functions of zooming the screen in and out and allowed pilots to see which Xr configuration was being flown during the encounter.

Pilots controlled the vehicle using two side inceptors and foot rudders. The left inceptor increased and decreased speed; this inceptor also contained two buttons that zoomed the Map Display in and out. The right-side inceptor increased left and right bank angles, allowing for left and right turns, and it increased and decreased vertical rates, allowing for climbs and descends. The right inceptor was also fitted with a button that disengaged and reengaged the Hover flight mode. Moving the right inceptor in any direction automatically transitioned the aircraft from autopilot to manual mode. Rudders only allowed for yaw control during Hover and slow-speed flight; slip control was automatically generated. Examples of the displays and controls are shown in Fig. 5.

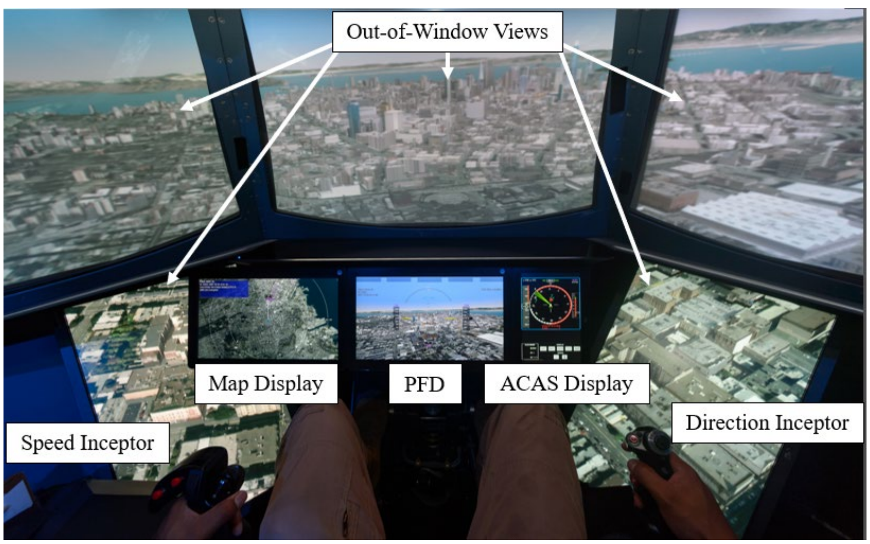


Fig. 5 Displays and controls of the rotorcraft cabin within the Vertical Motion Simulator.

E. Detect and Avoid System

During the study, version two of ACAS Xr (August 2022) provided alerting and guidance for intruder traffic. These prompts were delivered as aural cues along with visual text banners, guidance banding, and a unique traffic icon, which all changed based on the distances and trajectories of both ownship and intruder aircraft. When RAs were issued, they could be Horizontal (banding on the outer range ring), Vertical (banding on the vertical speed indicator), or Blended (banding on both the outer range ring and vertical speed indicator) and were accompanied by aural cues like "Turn Left," "Descend," or "Turn Left and Descend," respectively. Banding was red and green while RAs were active; pilots had to maneuver until their target track and vertical speed were clear of the red portions and fell within or beyond the green portions. See Fig. 6 for an example of a Blended RA. Pilots were also assumed to comply with RAs within five seconds and that they achieved a three-degree-per-second (i.e., standard rate) turn for Horizontal RAs and a vertical rate of +/- 1,000 feet per minute for Vertical RAs. Pilots were also expected to monitor a conflict and comply with RA updates, which could occur frequently and lead to reversals (i.e., RAs that change the direction of a turn), strengthenings (e.g., assigning wider target tracks), or Blended RAs (e.g., a "Turn Right" RA becoming "Turn Right and Climb" RA).

Fig. 6 Example of a Blended RA, which includes the RA icon, text banner, and red (avoidance) and green (target) horizontal and vertical banding. The "Turn Left and Descend" cue is provided audibly.

Version two of ACAS was developed allowing for two configurations that offered different sets of behaviors [11]; these configurations are referred to here as Collision Avoidance System (CAS) and Detect and Avoid (DAA). Both configurations share some similarities, such as the color schemes of background traffic (i.e., cyan) and the caution-level (i.e., yellow) and warning-level (i.e., red) alerts. However, the configurations diverge for factors like the meanings of traffic icons, elements present in the alerts, ways the alerts function, circumstances that cause them, and expected pilots' responses. Details are in Table 1 and the sections below.

Table 1 ACAS Xr Alerting Structures by Configuration

Traffic Icon	Configuration	
	CAS Alert Structure	***DAA Alert Structure***
	Resolution Advisory (RA) • *Pilot Actions*: Comply with RA within 5 seconds • *Maneuver Guidance*: Directive banding • *Aural Cues*: ○ "Climb, Climb" or "Descend, Descend" ○ "Turn Right, Turn Right" or "Turn Left, Turn Left"	Resolution Advisory (RA) • *Pilot Actions*: Comply with RA within 5 seconds • *Maneuver Guidance*: Directive banding • *Aural Cues*: ○ "Climb, Climb" or "Descend, Descend" ○ "Turn Right, Turn Right" or "Turn Left, Turn Left"
	Traffic Advisory (TA) • *Pilot Actions*: Monitor traffic for possible RA • *Maneuver Guidance*: None • *Aural Cues*: "Traffic, Traffic"	Corrective DAA Alert • *Pilot Actions*: Action required to remain well-clear • *Maneuver Guidance*: Suggestive banding • *Aural Cues*: "Traffic, Avoid"
	N/A	Preventive DAA Alert • *Pilot Actions*: Monitor traffic for possible increase in severity • *Maneuver Guidance*: None • *Aural Cues*: "Traffic, Monitor"
	N/A	Guidance Traffic • *Pilot Actions*: Monitor traffic for possible increase in severity • *Maneuver Guidance*: None • *Aural Cues*: None
	Basic Traffic • *Pilot Actions*: None • *Maneuver Guidance*: None • *Aural Cues*: None	Basic Traffic • *Pilot Actions*: None • *Maneuver Guidance*: None • *Aural Cues*: None

1. CAS Configuration

The CAS configuration is a legacy version of ACAS Xr that allows the system to behave similarly to TCAS II. CAS was built for crewed configurations operating under SAA principles. Basic background traffic icons are assigned to aircraft that do not pose an immediate threat. Traffic detected as a potential problem are assigned as Traffic Advisories (TAs); these TAs are intended for situational awareness only; they are shown as solid yellow chevrons and circles and provide the aural cue “Traffic, Traffic.” TAs are intended to attract attention to the airspace so that the pilot can attempt to visually acquire nearby traffic and plan accordingly in Cruise and Hover scenarios (Fig. 7). Should intruder traffic become an NMAC threat during Cruise and Hover scenarios, the CAS configuration issues RAs. Descend RAs are automatically suppressed below 750 feet above ground level (AGL) to avoid pilots descending too close to the terrain. During approaches into terminal areas, pilots are expected to switch ACAS to a ‘TA-Only’ mode to prevent nuisance alerts. By doing so, all RAs are suppressed, leaving surrounding aircraft labeled as Basic traffic or TAs. During TAs in the terminal area, pilots are expected to maneuver using their best judgment.

Fig. 7 Example of a TA. The advisory displays a caution-level icon and text banner. The “Traffic, Traffic” cue is provided audibly.

2. DAA Configuration

The DAA configuration behaves similarly to its uncrewed version, ACAS Xu, and provides caution-level guidance to maintain DAA well-clear. This guidance allows for an extra layer of situational awareness and risk mitigation. Similar to the CAS configuration, DAA shows background traffic as Basic. Basic aircraft become Guidance traffic if they operate close enough to the ownship to generate DAA guidance bands that do not intercept ownship’s current trajectory (i.e., it could become a DAA well-clear threat if the ownship or the intruder maneuvers in the other’s direction). A piece of traffic will appear as a Preventive DAA alert, shown as a solid-yellow chevron and hollow-yellow circle and accompanied by the “Traffic, Monitor” aural cue. Preventive alerts indicate that traffic is approximately 500 feet above or below ownship and are offered to advise pilots against vertical maneuvers. Traffic will register as a Corrective DAA alert if it is predicted to penetrate the DAA well-clear volume (defined for en-route encounters as 4000 feet laterally, 450 feet vertically, and a 35-second time buffer or ‘modified Tau’). These alerts share the same icons as TAs in the CAS condition; however, they are accompanied by the aural cue “Traffic, Avoid.” The alerts also share similar horizontal and vertical banding as RAs; however, Corrective banding is yellow, suggestive, and includes airspace guidance (i.e., overlaid on the airspeed indicator) for version 2 of ACAS Xr. See Fig. 8 for an example of a DAA Corrective alert. Pilots are expected to begin evasive maneuvering during these alerts, using the banding to inform their decisions. During Cruise and Hover scenarios at low altitudes, ACAS Xr regards the terrain as an intruder in the DAA condition, which allows the ownship to travel closer to the ground than in the CAS configuration. In the terminal area, defined as a landing zone five nautical miles laterally and 2000 feet vertically of the ownship, DAA alerting and Horizontal RAs are suppressed against terminal-area-designated intruding aircraft. These behaviors meet terminal-area requirements, as prescribed by [10] and are intended to guide the pilot to climb, level off, or continue descending for a landing.

Fig. 8 Example of a DAA Corrective alert. The alert displays the caution-level icon, text banner, and yellow horizontal, vertical, and airspeed guidance bands. The "Traffic, Avoid" cue is provided audibly.

F. Phase of Flight

Different types of conflicts needed to be tested for each phase of flight, so ten unique encounters were created for each phase. Therefore, the geometries, altitudes, and behaviors of both ownship and intruders differed slightly across the conditions.

1. Cruise

Cruise encounters were designed to test en-route flight. These encounters started at 110 knots indicated airspeed (IAS) and between 500-1500 feet MSL. Encounters initialized with the vehicle in auto-pilot mode, at mission altitude and speed. Pilots would respond to all alerting manually by operating the right inceptor, which would also automatically disengage the autopilot mode.

2. Hover

Hover encounters were designed to test low-speed flight. These encounters started at 10 knots IAS and between 500-1500 feet MSL. Unlike cruise encounters, pilots had to press a 'Hover disengage' thumb button on the right inceptor before they could begin to accelerate (via the left inceptor). Pilots made lateral and vertical maneuvers with the right inceptor. As with the cruise scenarios, the hover encounters initialized in autopilot mode, at mission altitude and speed.

3. Approach

Approach scenarios were designed to test terminal-area operations. These encounters started several miles from a vertiport at 70 knots IAS and between 700-1100 feet MSL, with the aircraft established on a six-degree, descending approach path into a landing site.

G. Procedure

Pilots spent two days at the VMS facility. Participants were trained on and experienced only one ACAS configuration (i.e., CAS or DAA) on a given day; this arrangement was an attempt to minimize mode confusion that could come with experiencing both ACAS configurations on a single day. Days began with the dissemination and completion of informed consent and demographics forms. Afterward, pilots were led through sessions of classroom instruction and hands-on training lasting approximately two hours. Classroom discussions used slideshows to detail aspects of the project (e.g., justifications and objectives), ACAS Xr (e.g., overview and configuration), the simulator (e.g., vehicle model, displays, and controls), and expectations of the pilots. Hands-on training allowed the pilots to fly the simulator during full-motion activation; researchers provided practice encounters that would familiarize pilots with the vehicle, simulation environment, phases of flight, and aircraft conflicts that would be encountered. Pilots continued this handling training until they showed acceptable confidence and competence with the systems.

During data collection, pilots flew scenarios that initialized mid-flight. The pilots' ownship started at its mission altitude while flying from waypoint to waypoint in autopilot mode. Intruder conflicts began one to three minutes into scenarios. Pilots were instructed to use ACAS Xr's alerting and guidance to deconflict from the intruders unless this information was deemed unsafe. Inceptors were used to disengage the autopilot and manually execute the maneuvers. For the CAS configuration, pilots were trained to use TAs for situational awareness only, trying to first visually acquire the intruders and then maneuver only after the onset of the following RAs. For the DAA configuration, pilots were instructed to maneuver after the onset of the caution-level alert, using suggestive guidance to help inform their decisions. Once ACAS delivered RAs in either configuration, pilots were required to comply with the directions within five seconds of the initial RA and two and a half seconds for subsequent RAs—unless the pilots felt that the maneuvers provided by ACAS were unsafe. Finally, participants were instructed to maneuver their vehicle back to its original course once the alerts had cleared from the displays and the pilots felt it was safe. Encounters were concluded once the pilots had begun turning the aircraft back to its original course. Pilots completed three phase-of-flight trials (i.e., Cruise, Hover, and Approach) containing 10 encounters each (30 for each day and 60 for each participant). Each data-collection encounter lasted approximately five minutes, resulting in roughly 50 minutes per trial, two and a half hours per day, and five hours per participant. Pilots completed questionnaires throughout both days and ended their participation on day two with a debrief.

III. Experimental Design

A. Variables

The present study utilized two within-subjects variables. Variables of interest were ACAS Xr configuration and phase of flight. The configuration variable contained two levels: CAS and DAA. The phase of flight variable contained three levels: Cruise, Hover, and Approach. Encounters were counterbalanced using the Latin Square design, which was then used to construct run schedules for each pilot. These schedules are shown in Table 2. Each phase of flight was flown under both configurations, and the two configurations were blocked by day.

Table 2 Data Collection Run Matrix

Pilot	Day	Trial 1	Trial 2	Trial 3
1	1	CAS Mode_Cruise	CAS Mode_Approach	CAS Mode_Hover
1	2	DAA Mode_Hover	DAA Mode_Approach	DAA Mode_Cruise
2	1	CAS Mode_Cruise	CAS Mode_Hover	CAS Mode_Approach
2	2	DAA Mode_Approach	DAA Mode_Hover	DAA Mode_Cruise
3	1	CAS Mode_Hover	CAS Mode_Cruise	CAS Mode_Approach
3	2	DAA Mode_Approach	DAA Mode_Cruise	DAA Mode_Hover
4	1	DAA Mode_Cruise	DAA Mode_Approach	DAA Mode_Hover
4	2	CAS Mode_Hover	CAS Mode_Approach	CAS Mode_Cruise
5	1	DAA Mode_Cruise	DAA Mode_Hover	DAA Mode_Approach
5	2	CAS Mode_Approach	CAS Mode_Hover	CAS Mode_Cruise
6	1	DAA Mode_Hover	DAA Mode_Cruise	DAA Mode_Approach
6	2	CAS Mode_Approach	CAS Mode_Cruise	CAS Mode_Hover

B. Metrics and Analyses

Pilot impressions were collected using questionnaires. Post-encounter questionnaires were delivered after each encounter. Post-trial questionnaires were delivered after pilots completed 10 encounters within a specific flight phase. Post-block questionnaires were delivered after the 30 encounters for the day (i.e., all encounters in a particular ACAS configuration) were completed. Finally, post-simulation questionnaires were delivered after pilots completed all 60 encounters over the two days. Questionnaires contained combinations of Likert scales, multiple choice, and open-ended responses. Following the post-simulation questionnaire, additional pilot feedback was collected with a post-simulation debrief, using open-ended questions to encourage a guided conversation about their experiences during the simulation. These subjective metrics explored the pilots' opinions of the alerting and guidance from ACAS and their general experiences during the study. Pilot feedback was collected to inform the researchers of the usefulness, effectiveness, acceptability, and preferences of ACAS Xr's corrective-level and warning-level alerting and guidance across configurations and phases of flight. Objective metrics were also collected and included pilot response times, choices of maneuvers, compliances of RAs, and different types of losses of separation. These objective results were published separately [17].

Metrics were not directly comparable using inferential statistics. One reason is that the DAA configuration initially provided DAA alerting and guidance during a conflict, and pilots were instructed to maneuver in response to these alerts. Pilots were then expected to comply with RAs only if conflicts could not be deconflicted during the DAA maneuvers. By contrast, the CAS configuration initially provided pilots TAs during a conflict. Pilots were trained to refrain from maneuvering during the TAs, but instead begin maneuvers when complying with RAs. Additionally, encounters were designed differently for each flight phase to accommodate the conflicts of interest for these phases.

Therefore, descriptive statistics are offered to characterize pilots' impressions using comparisons of means, standard errors, percentages, and ratios. These metrics are delivered for both configurations and phase of flight.

IV. Results

When responding to a 5-point scale (1 = "Strongly Disagree"; 5 = "Strongly Agree"), pilots said that they received sufficient training ($M = 4.83$, $SE = 0.17$) for the study. All pilots (6/6) reported that learning interference may have affected their use of the controls. Namely, pilots agreed that seeing traffic out of the window impacted how they responded to ACAS Xr ($M = 4.00$, $SE = 0.52$). Regardless, pilots generally regarded ACAS Xr positively on scales of agreeability, time (e.g., 1 = "Far Too Early"; 5 = "Far Too Late"), and size (e.g., 1 = "Far Too Small"; 5 = "Far Too Large"), as shown in Table 3.

Table 3 Pilot subjective ratings

Criteria	Configuration	Mean	Standard Error	Scale Answer
Acceptability	CAS	4.35	0.17	"Somewhat Agree"
	DAA	4.35	0.18	"Somewhat Agree"
Sufficiency to maintain separation	CAS	4.28	0.17	"Somewhat Agree"
	DAA	4.50	0.22	"Strongly Agree"
Alerts helped resolve encounters	CAS	4.28	0.07	"Somewhat Agree"
	DAA	4.17	0.80	"Somewhat Agree"
Timing of alerts	CAS	3.18	0.05	"Perfectly Timed"
	DAA	3.24	0.04	"Perfectly Timed"
Duration of alerts	CAS	3.18	0.05	"Perfect Length"
	DAA	3.24	0.04	"Perfect Length"
Size of proposed maneuvers	CAS	3.04	0.04	"Perfectly Sized"
	DAA	2.94	0.05	"Perfectly Sized"
Comfortable complying with RAs at low altitudes	CAS	3.83	0.40	"Somewhat Agree"
	DAA	4.00	0.52	"Somewhat Agree"

A. Configurations

1. DAA

The DAA configuration included caution-level DAA guidance in the horizontal, vertical, and speed dimensions. Pilots reported that the DAA guidance was effective for maintaining separation ($M = 4.50$, $SE = 0.22$), and all pilots (6/6) said that the banding affected their decisions when maneuvering. The most useful elements were the aural cues ($M = 4.67$, $SE = 0.21$), vertical banding ($M = 4.33$, $SE = 0.21$), and horizontal banding ($M = 4.17$, $SE = 0.48$). The least favorable ratings were given to the speed banding ($M = 3.17$, $SE = 0.48$) and text banners ($M = 3.83$, $SE = 0.60$) that were also provided during the alerts.

2. CAS & RAs

RAs constituted the sole type of alerts against which pilots could maneuver during the Cruise and Hover phases of flight in the CAS condition. Like the DAA condition, pilots reported that the RAs in the CAS configuration were generally effective for maintaining separation ($M = 3.83$, $SE = 0.40$). Most pilots (5/6) were comfortable with switching CAS to a TA-only mode while entering the terminal area. Pilots found the RA alerts, however, the most effective for maintaining distance between aircraft in the CAS condition. Pilots reported that the five-second expectation to respond to RAs was reasonable ($M = 4.83$, $SE = 0.31$) and that the most useful collision avoidance elements were Vertical RAs ($M = 4.50$, $SE = 0.34$), Horizontal RAs ($M = 4.67$, $SE = 0.21$), Blended RAs ($M = 4.67$, $SE = 0.21$), and RA aural cues ($M = 4.67$, $SE = 0.42$). Although they were not provided for this study, pilots also said that clear-of-conflict aural cues would have also been nice to receive ($M = 4.00$, $SE = 0.37$). Lower ratings were provided for text banners ($M = 3.33$, $SE = 0.42$). Furthermore, most pilots (4/6) found the 1000-foot-per-minute vertical rates were unacceptable, suggesting a 500-foot-per-minute default rate instead. Despite the usefulness of RAs in general, most pilots (4/6) also admitted to disregarding some RAs due to inappropriate guidance (e.g., too close to terrain or insufficient separation from traffic).

B. Phases of Flight

These findings are specific to different phases of flight. Pilots noted that the alerting and guidance provided by ACAS Xr was achievable by the NASA Lift Plus Cruise (NLPC) model (CAS: $M = 4.39$, $SE = 0.24$; DAA: $M = 4.61$, *SE* = 0.44) and would be acceptable to other airspace users, like air traffic control and nearby aircraft, for all phases of flight (CAS: *M* = 4.28, *SE* = 0.18; DAA: *M* = 4.06, *SE* = 0.22). Appropriate alerting and guidance was also given for both configurations in Cruise (CAS: *M* = 4.50, *SE* = 0.22; DAA: *M* = 4.67, *SE* = 0.21) and Hover (CAS: *M* = 4.17, *SE* = 0.17; DAA: *M* = 4.00, *SE* = 0.44); however, there was a noticeable drop in pilots' ratings in the Approach phase for DAA (*M* = 3.83, *SE* = 0.40) compared to CAS (*M* = 4.83, *SE* = 0.17). Similar drops in ratings were seen for 'sufficient level of alerting and guidance,' which was positive for Cruise (CAS: *M* = 4.67, *SE* = 0.21; DAA: *M* = 4.33, *SE* = 0.49) but was lower for CAS during Hover (CAS: *M* = 3.83, *SE* = 0.40; DAA: *M* = 4.00, *SE* = 0.44) and DAA during Approach (CAS: *M* = 4.17, *SE* = 0.40; DAA: *M* = 3.67, *SE* = 0.42); see Fig. 9.

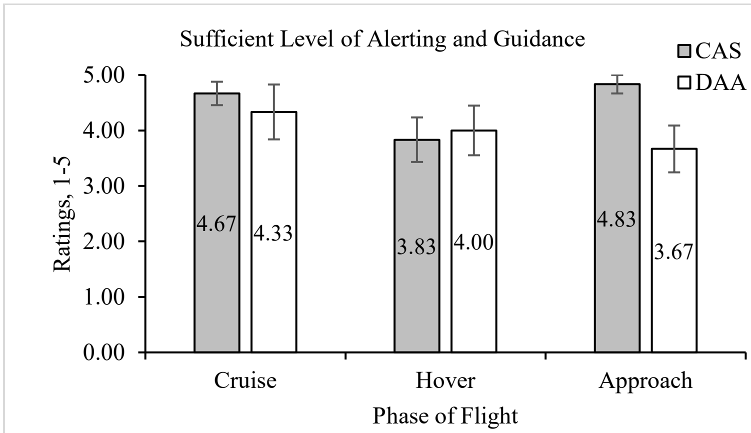


Fig. 9 Sufficient level of alerting and guidance for all flight phases.

C. Pilot preferences

Pilots were asked what level of alerting they felt was most appropriate in each phase of flight (Cruise, Hover, and Approach). Alert options were: DAA alerts only, DAA alerts and RAs, TAs only, TAs and RAs, or RAs only. Most pilots (5/6) responded that DAA alerts and RAs (i.e., the DAA configuration) were the most appropriate in Cruise. In Hover, pilots were split (3/3 each) in their response, with half preferring TAs and RAs and the other half preferring RAs only. Pilots had the least consensus when responding for Approach. Each alert option received at least one vote, except for TAs Only (0/6), which is how the CAS configuration operates in the terminal area. Pilots also reported that, in current-day VFR operations, DAA (*M* = 4.17, *SE* = 0.31) and CAS (*M* = 4.17, *SE* = 0.31) were useful. However, more pilots said that CAS (4/6) was the *best* suited for VFR. When choosing only one configuration to fly with, half of pilots chose DAA, and half chose CAS.

V. Discussion & Conclusion

The present paper reports on pilot evaluations of ACAS Xr's guidance in a full-motion eVTOL simulator. The two conditions explored were ACAS Xr configurations (i.e., CAS and DAA) and phases of flight (i.e., Cruise, Hover, and Approach). To accomplish this objective, six helicopter pilots flew in a simulated San Francisco environment during VFR air taxi operations and used customized displays (i.e., Map Display, PFD, and ACAS Xr Display) and controls (i.e., two side inceptors and foot rudders) to maneuver against 60 scripted traffic encounters. Subjective ratings and other feedback were collected from questionnaires that researchers delivered after each encounter, trial (i.e., 10 encounters within a specific flight phase), block (i.e., 30 encounters within a specific ACAS configuration), and simulation (i.e., all 60 encounters over two days). Additional pilot evaluations were obtained with a post-simulation debrief. This procedure allowed the researchers to gather data regarding operational acceptability for ACAS Xr's corrective-level and warning-level alerting and guidance across the configurations and phases of flight.

Pilots predominantly found the alerting and guidance provided by ACAS Xr useful, effective, and acceptable. Results showed that DAA alerting and guidance effectively maintained sufficient separation and was the preferred alerting configuration in Cruise. Pilots valued the banding and aural cues because these indicators helped the pilots make faster and more informed decisions. Even though DAA guidance in the vertical and horizontal dimensions was useful, pilots felt that the speed guidance provided little utility, indicating that they rarely used it. Most RAs (Horizontal, Vertical, and Blended) were deemed effective. Pilots disagreed with the current vertical rate and suggested that 500 feet per minute is more appropriate for rotorcraft. Additionally, Level-Off RAs were problematic because they caused the ownship to come too close to the intruder or terrain, especially during Hover and Approach encounters. Feedback indicated that these Level-Off RAs should instead be replaced with Climb or Descend RAs—especially in a terminal environment when a pilot may be expected to land or perform a go-around procedure. Pilots reported that both CAS and DAA configurations were useful in current-day VFR operations, with a slight preference for CAS. Pilots were divided on which ACAS configuration they preferred if forced to choose one: Half of the pilots chose the additional situational awareness of the DAA configuration, and half liked the simplicity and familiarity of the CAS configuration.

Alerting and guidance performed the best during Cruise flights, but further research and development are still needed for ACAS Xr to provide safe aid during Hover (i.e., low speed) and Approach (i.e., terminal-area) conflicts. Pilots rated ACAS Xr the least effective during Hover encounters due to the time-consuming procedures involved in disengaging Hover and accelerating; pilots added that ACAS's alerting and guidance would perform better if it factored these procedures into its alerting to give pilots more time to complete them. Additionally, the procedure led to confusion and longer response times in Hover. The Level-Off RAs were considered problematic in Hover. These problems were often due to ACAS Xr detecting the intruder above the ownship and terrain below the ownship, which would lead to ACAS restricting climb or descend RAs. In many cases, Horizontal RAs would also be absent, leading the pilots to maneuver against Level-Off RAs to resolve conflicts. In some cases, pilots disregarded Descend RAs in the DAA mode due to how close the ownship came to terrain. During Approach scenarios, the lack of DAA guidance during the DAA configuration meant that pilots lost DAA well-clear before maneuvering for RAs. Many warning-level alerts issued in the terminal environment were Level-Off RAs, which directed pilots to continue flying towards the intruder. Pilots, therefore, preferred maneuvers that instructed them to climb or descend. Most noncompliances occurred in the Hover or Approach scenarios for the reasons mentioned above. Additionally, pilots' performances (e.g., reaction time, losses of well-clear, NMACs, etc.) suffered more during these phases of flight as reported by [17].

Pilots declared that they received enough training for the simulation. Still, pilots also said that more training would be needed before operators could fly the NLPC model in real-world operations. Pilots added that muscle memory, or interference, played a role in their difficulty with the controls. To be specific, flight training for their particular aircraft types made them want to control the NLPC model in the same ways; even after training in the simulator, pilots still felt the urge to fly the eVTOL model like a helicopter. Pilots also reported that this interference was most notable during transition periods. During these periods, the aircraft would go from Hover mode to Cruise, and therefore the handling of the NLPC model would change from a helicopter-type control feel to fixed-wing. This rapid switching of handling took a lot of work to get used to. Pilots finally reported that additional training could remediate this interference, and new UAM operators would have an advantage if their initial training was on such systems.

Despite being trained to respond to conflicts by using ACAS Xr, pilots agreed that seeing traffic out of the window impacted how they responded to the alerting and guidance. The reason for this impact was the pilots' desire to visually acquire the intruder before maneuvering. This impulse sometimes led to pilots disregarding alerting and guidance and instead maneuvering based on what they could see out of the window. Pilots argued that this is a reason why aural cues were considered necessary. These audible prompts attract pilots' attention during VFR operations when pilots' vision is normally focused outside the aircraft. Continuing along this line of reasoning, pilots also desired clear-of-conflict aural cues, which were not provided for this study. Similarly, alert banners were not regarded as necessary because pilots' attentions were grabbed by the aural alerts and directed by the guidance and directive banding.

Limitations of this study include the lack of some real-world elements as well as the simulation's resolution. Notably, pilots were not exposed to elements encountered in the National Airspace, such as ATC coordination and background traffic. Furthermore, the simulation relied on pristine sensor data input into ACAS Xr, sparing pilots the challenges of sensor noise. Moreover, pilots noted that the screen resolution within their cabin led to closer approaches to intruding aircraft compared to real-flight scenarios, particularly when positive visual contact was required (e.g., in TA-only mode during Approach scenarios).

Just as past simulations have contributed to the current study, insights gleaned from this endeavor have shaped the development and implementation of a follow-on flight test [18]. In the test, ACAS Xr was installed on a helicopter and flown against a live intruder under test conditions that closely mirrored the present study (CAS and DAA configurations, low speed encounters, and terminal area-like operations).

Acknowledgments

The authors thank the Airspace Operations and Safety Program's Advanced Air Mobility project for funding this work. The authors also wish to acknowledge Thomas Quinonez and Matthew Blanken of NASA ARC for the hardware and software development and support during the study.

References

[1] Johnson, W., Silva, C., and Solis, R., "Concept Vehicles for VTOL Air Taxi Operations," *AHS Technical Conference on Aeromechanics Design for Transformative Vertical Flight*, San Francisco, CA, 2018.

[2] Wing, D. J., Chancey, E. T., Politowicz, M. S., and Ballin, M., "Achieving Resilient In-Flight Performance for Advanced Air Mobility through Simplified Vehicle Operations," *AIAA AVIATION 2020 Forum*, Virtual, 2020. doi: 10.2514/6.2020-2915

[3] Federal Aviation Administration, "Urban Air Mobility (UAM) Concept of Operations," Report Version 2.0, Washington, DC, 2023.

[4] Federal Aviation Administration, "Pilots' Role in Collision Avoidance," Report AC 90-48D, 2016.

[5] Cohen, A., and Shaheen, S., "Urban Air Mobility: Opportunities and Obstacles," Transportation Sustainability Research Center, Berkeley, CA, 2021. doi: 10.1016/B978-0-08-102671-7.10764-X

[6] Scheff, S., "State of the Industry: UAS Sensor Review (No. NASA/CR-20210026446)," Moffett Field, CA, 2021.

[7] Kochenderfer, M. J., Holland, J. E., and Chryssanthacopoulos, J. P., "Next-Generation Airborne Collision Avoidance System," Lincoln Laboratory Journal [online journal], Vol. 19, No. 1, 2023, pp. 17–33, URL: https://www.ll.mit.edu/sites/default/files/page/doc/2018-05/19_1_1_Kochenderfer.pdf [retrieved 4 January 2023].

[8] Lincoln Laboratory, "Airborne Collision Avoidance System X," Tech Notes Database [online database], URL: https://apps.dtic.mil/sti/pdfs/ADA625750.pdf [retrieved 15 November 2022].

[9] Katz, S. M., Kochenderfer, M, J., Alvarex, L. E., Owen, M., Wu, S., Brittain, M., and Das, H., "Collision Risk and Operational Impact of Speed Change Advisories as Aircraft Collision Avoidance Maneuvers," *AIAA AVIATION 2022 Forum*, Chicago, IL, 2022. doi: 10.48550/arXiv.2204.14250

[10] RTCA, "Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems Revision B (No. DO-365B)," Washington, DC, 2021.

[11] Federal Aviation Administration, "Concept of Use for the Airborne Collision Avoidance System for Rotorcraft (Xr)," Report ACAS_RPR_23_002_V3R0, 2022.

[12] Rorie, R. C., Smith, C. L., Sadler, G. G., Monk, K. J., Tyson, T. L., and Keeler, J. N., "A Human-in-the-Loop Evaluation of ACAS XU," *AIAA/IEEE 39th Digital Avionics Systems Conference (DASC)*, San Antonio, TX, 2020, pp. 1–10. doi: 10.1109/DASC50938.2020.9256618

[13] Smith, C. L., Rorie, R. C., Monk, K. J., Keeler, J., and Sadler, G. G., "UAS Pilot Assessments of Display and Alerting for the Airborne Collision Avoidance System XU," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 64, No. 1, 2020, pp. 159–163. doi: 10.1177/1071181320641040

[14] Smith, C. L., Rorie, R. C., Chandarana, M., Tyson, T. L., and Keeler, J., "Helicopter Pilot Assessments of the Airborne Collision Avoidance System XR with Automated Maneuvering," *AIAA AVIATION 2023 Forum*, San Diego, CA, 2023. doi: 10.2514/6.2023-3683

[15] Kaneshige. K., Lombaerts, T., Shish, K., and Feary, M., "Command and Control Concepts for a Lift Plus Cruise Electric Vertical Takeoff and Landing Vehicle," *AIAA AVIATION 2023 Forum*, San Diego, CA, 2023. doi: 10.2514/6.2023-3910

[16] Aponso, B. L., Beard, S. D., and Schroeder, J. A., "The NASA Ames Vertical Motion Simulator – A Facility Engineered for Realism," *Royal Aeronautical Society Spring 2009 Flight Simulation Conference*, London, UK, 2009.

[17] Rorie, R. C., Smith, C. L., Mitchell, M., and Schmitz, C., "Assessing Helicopter Pilots' Detect and Avoid and Collision Avoidance Performance with ACAS Xr," *42nd AIAA/IEEE Digital Avionics Systems Conference (DASC)*, Barcelona, Spain, 2023. doi: 10.1109/DASC58513.2023.10311279

[18] Rorie, R. C., and Smith, C. L., "Detect and Avoid and Collision Avoidance Flight Test Results with ACAS Xr," *43rd AIAA/IEEE Digital Avionics Systems Conference (DASC)*, San Diego, CA, 2024.