Assessing Helicopter Pilots' Detect and Avoid and Collision Avoidance Performance with ACAS Xr

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Abstract*—The latest variant of the Federal Aviation Administration's Airborne Collision Avoidance System (ACAS X) is being designed for both crewed and uncrewed rotorcraft. Referred to as ACAS Xr, the system joins a suite of other ACAS X variants poised to replace the second iteration of the Traffic Alert and Collision Avoidance System (TCAS II). ACAS Xr is tuned to support current-day helicopter platforms as well as electric Vertical Takeoff and Landing (eVTOL) vehicles that are still under development. Given this flexibility, ACAS Xr may be used by helicopter crews currently in operation or by remotely-operated eVTOL aircraft in the emerging Advanced Air Mobility (AAM) market. To cover the range of potential uses, two distinct configurations are being proposed for ACAS Xr: Collision Avoidance System (CAS) and Detect and Avoid (DAA). Under the CAS configuration, ACAS Xr provides minimal caution-level alerting but issues directive warning-level alerting and guidance. The DAA configuration, by contrast, provides caution-level alerting and guidance, in addition to the warning-level alerting and guidance. The current study was performed as part of the National Aeronautics and Space Administration's AAM project. Six helicopter pilots were recruited to fly a variety of scripted traffic scenarios in a full-motion, crewed eVTOL simulator. Participants flew 60 encounters over two days, reacting to pre-recorded intruder aircraft that were scripted to fly into the participant's aircraft from different approach angles, relative altitudes, and during different phases of flight. The pilots flew half of the encounters with the CAS configuration and half with the DAA configuration. Within each block of 30 encounters, pilots experienced 10 conflicts while in cruise, 10 in hover, and 10 while on approach to a heliport. Results showed that pilot response times were consistently under 5 seconds for RAs and under 10 seconds for DAA alerts, when present, during all three phases of flight. Unsurprisingly, the DAA configuration was associated with lower rates of en-route and high-severity losses of DAA well clear compared to the CAS configuration in all phases of flight except for the terminal area. Rates of losses of DAA well clear were found to be substantially higher in the Hover scenario compared to Cruise. Pilots failed to fully comply with RAs at a rate of 0.10-0.18 in all conditions except for the DAA configuration in the Hover scenario, which was associated with a higher non-compliance rate of 0.4 due to Descend RAs issued at low altitudes. The implications of these results with regard to the ongoing development of ACAS Xr are discussed.

Keywords— detect and avoid, collision avoidance, ACAS X, advanced air mobility

I. INTRODUCTION

Recent advancements in aircraft design, air traffic management, and automation capabilities have resulted in the emergence of a new airspace operational concept referred to as Advanced Air Mobility (AAM) [1]. The general aim of AAM is to develop an air transportation ecosystem that connects traditionally underserved areas, namely local, regional, and urban environments. The AAM community is pursuing levels of maturity that could accommodate hundreds of simultaneous operations in a single area, which will require the development of highly automated traffic and vehicle management systems to support safe operations. These new airspace concepts will leverage innovative vehicle designs and capabilities, such as electric Vertical Takeoff and Landing (eVTOL), which may allow for more flexible operating environments and more efficient operational tempos than have previously been possible. The broad scope of the AAM vision will likely result in a diverse set of operators, which could include a mix of current-day helicopters with onboard pilots, remotely-piloted eVTOL aircraft, and aircraft supervisors monitoring multiple highly-automated vehicles from the ground simultaneously.

As with legacy aviation, a key capability for AAM operators will be the ability to ensure both onboard and remote pilots can reliably maintain well clear and avoid collision hazards. Currently, all onboard pilots maintain well clear by way of "see and avoid," which requires pilots to avoid potential collision hazards through visual contact [2]. Some present-day operators are also equipped with the second version of the Traffic Alert and Collision Avoidance System (TCAS II), which provides an additional layer of safety against midair collisions through visual and aural alerting presented on the flight deck. Remote pilots, by contrast, maintain well clear through the use of a Detect and Avoid (DAA) system, the requirements for which have been published, and revised, by RTCA Special Committee 228 (SC-228) [3]. A DAA system quantifies well clear, a traditionally subjective concept, in order to provide alerting and guidance against intruders that are predicted to violate it. Operators of Unmanned Aircraft Systems (UAS) may optionally include Collision Avoidance System (CAS) capabilities by also integrating TCAS II or its next-generation successor, the Airborne Collision Avoidance System X for large UAS, referred to as ACAS Xu [4]. As with traditional aircraft that are equipped with TCAS II, adding a CAS capability to UAS provides an additional level of protection against midair collision.

While the development efforts behind TCAS II, DAA systems, and ACAS Xu were extensive, their applicability to AAM is limited. TCAS II has known “blind spots” directly above and below the aircraft, which are not a significant safety concern for fixed-wing aircraft, but become a severe limitation in the context of rotorcraft [5]. Similarly, DAA systems and ACAS Xu were developed specifically for remote pilots of fixed-wing aircraft and do not account for rotorcraft flight characteristics. To address the lack of dedicated DAA and CAS technologies for helicopters and eVTOL platforms, the Federal Aviation Administration (FAA) and RTCA Special Committee 147 (SC-147) initiated the development of ACAS Xr, the rotorcraft variant of ACAS X [6]. This version of the system is designed to accommodate the unique aspects of rotorcraft, such as limited vertical rate performance and the ability to fly much closer to the ground and at much slower speeds than fixed-wing aircraft. ACAS Xr is being designed to support current-day helicopter operations with an onboard pilot as well as remotely-piloted eVTOL operations that are being proposed under AAM [5].

ACAS Xr can target these two distinct concepts of operation by providing two separate configurations: a CAS configuration and a DAA configuration [5]. The CAS configuration is designed for operations with a pilot onboard, where they can rely on their ability to see and avoid and only have a need for the collision avoidance functionality. The CAS configuration behaves similarly to TCAS II by providing minimal caution-level alerting but issuing directive warning-level alerting and guidance. The caution alert, referred to as a Traffic Advisory (TA), is only intended to attract the pilot’s attention to prepare them for an impending warning alert, referred to as a Resolution Advisory (RA). Pilots are expected to immediately comply with RAs in order to avoid a near midair collision (NMAC). ACAS Xr (and ACAS Xu) issue Horizontal and “Blended” RAs, in addition to Vertical RAs, which are the only type of RAs issued by TCAS II. Whereas Vertical RAs command a target vertical speed, Horizontal RAs command a target track, and Blended RAs command a target track and target vertical speed simultaneously.

The DAA configuration is designed primarily for UAS operations, but it could be adopted by onboard helicopter and eVTOL pilots to increase their situation awareness and reduce the likelihood of receiving RAs. The DAA configuration has two caution-level DAA alerts (i.e., Preventive and Corrective) as well as caution-level guidance “banding”. The DAA banding is intended to be used by pilots to determine how to maneuver to prevent a loss of DAA well clear and, in doing so, prevent RAs and NMACs from occurring in the first place. The DAA configuration also includes the same RAs that are present in the CAS configuration, should pilots be unable to maintain DAA well clear against an intruder.

The CAS and DAA configurations also behave differently at lower altitudes and when flying in the terminal environment. The CAS configuration adopts TCAS II’s methodology at low altitudes by using an explicit cut-off altitude for Descend RAs (750 feet Above Ground Level [AGL]), below which Descend RAs are inhibited. The DAA configuration, alternatively, manages Descend RAs at lower altitudes with a Ground Point Obstacle Awareness (GPOA) feature. Rather than an explicit threshold, the GPOA function treats the ground as an intruder and takes its relative position into account when generating guidance. Practically, this means that the DAA configuration may permit Descend RAs to continue closer to the ground than the CAS configuration.

In the terminal environment, the CAS configuration requires the pilot to switch ACAS Xr from the nominal operating mode into a “TA Only” operating mode to reduce the likelihood of nuisance RAs. The TA Only mode suppresses RAs entirely, limiting all alerting to TAs, regardless of the severity of the conflict. This is similar to TCAS II, which automatically switches to TA Only mode below 1000 feet AGL. A manual switch is deemed necessary for ACAS Xr since rotorcraft routinely fly below 1000 feet AGL outside of the terminal environment. Conversely, ACAS Xr’s DAA configuration automatically suppresses caution-level alerting and guidance, as well as Horizontal RAs, against intruders in the terminal area. Terminal area intruders are also subject to a smaller DAA well clear volume due to the tight, coordinated spacing around airports. The modifications to the alerting and DAA well clear definition in the DAA configuration are designed to ensure remote pilots are appropriately alerted to genuine conflicts near the airport and are provided with guidance that directs the pilot to either climb (i.e., perform the missed approach), level-off, or continue to land. While ACAS Xr handles terminal area intruders separately from en-route intruders, a process external to ACAS Xr is needed to identify and flag intruders as within the DAA terminal area.

Multiple human-in-the-loop simulations have been conducted with ACAS Xu and ACAS Xr. The earlier work with ACAS Xu focused on the novel presentation of Horizontal and Blended RAs in the context of large, fixed-wing UAS operating under Instrument Flight Rules (IFR) in Class E airspace [7-9]. Those studies found that ACAS Xr performed well overall, but that certain accommodations needed to be made to promote pilot acceptability. These accommodations included reducing the frequency of Horizontal RA updates and simplifying the method by which pilots could enter and upload RA maneuvers to achieve the five-second response time window allocated by ACAS Xu.

A more recent study utilized a fixed-based eVTOL simulator to examine pilots’ interactions with, and perceptions of, ACAS Xr while operating the aircraft en-route under Visual Flight Rules (VFR) [10]. The simulation varied whether pilots responded to DAA alerts or to RAs. When responding to RAs, the researchers also varied whether the commanded maneuvers were executed automatically by the vehicle or manually by the pilot. The study found no significant impact of the automation variable on overall performance but did note cases where pilots did not fully comply with ACAS Xr RAs due either to terrain proximity or to excessive updating of Horizontal RAs.

The present effort was conducted under the National Aeronautics and Space Administration’s (NASA) AAM Project, as part of its Automated Flight and Contingency

Management (AFCM) Sub-Project. The study was designed to build on the previous ACAS Xr simulation by incorporating a higher level of simulation fidelity and broadening the operational context. Increased fidelity was achieved through the use of a full-motion simulator capable of high-fidelity out-the-window visuals that include terrain, obstacles, and aircraft. The operational context was expanded to include encounters while the ownship was in a hover and while it was performing a straight-in approach. This is notable since all earlier work with ACAS Xu and ACAS Xr has been limited to en-route operations. Pilots flew these different phases of flight with both ACAS Xr configurations – CAS and DAA – to assess the full range of ACAS Xr functionality. While the DAA configuration is tuned to remote operations, an open question is if, and to what extent, it could benefit onboard rotorcraft pilots.

II. Method

A. Experimental Design

The present study utilized two within-subjects variables, phase of flight and ACAS Xr configuration. The phase of flight variable had three levels – Cruise, Hover, and Approach. In the Cruise scenarios, the aircraft initialized at 110 knots true airspeed between 500-1500 feet Mean Sea Level (MSL). In the Hover scenarios, the aircraft initialized within the same altitude block but at 10 knots true airspeed. In the Approach scenarios, the aircraft initialized several nautical miles from the Initial Approach Fix (IAF) on a straight-in approach into a simulated vertiport. Approach scenarios started the vehicle at 70 knots true airspeed at an altitude between 700-1100 feet MSL and established on a 6° glideslope. In all three scenarios, the participants experienced a traffic conflict 1-3 minutes into the run, while the aircraft was still within the associated phase of flight.

The second variable, ACAS Xr configuration, had two levels – the Collision Avoidance System (CAS) configuration and the Detect and Avoid (DAA) configuration. As detailed above, these two ACAS Xr configurations differ in three distinct ways: the level of caution-level alerting and guidance, terminal area RA behavior, and low-altitude RA behavior. See Table 1 for a list of each configuration's key features.

The current study blocked the presentation of the scenarios by ACAS Xr configuration to reduce the likelihood of mode confusion. Half of the pilots experienced the CAS configuration first and half experienced the DAA configuration first. All three phases of flight were presented within each ACAS Xr configuration. Their order of presentation was counterbalanced to the extent possible given the limited number of participants recruited for the present study.

B. Participants

Six participants were recruited for this simulation. All participants were male and averaged 51 years of age (*SE* = 4 years). Participants were required to have a private helicopter pilot license and reported an average of 4,542 flight hours on helicopters. Five of the participants also had experience flying fixed-wing aircraft and were rated for IFR operations. Four of the participants rated themselves as familiar with TCAS II.

TABLE I. ACAS Xr Configuration Key Features

	Configuration	
Features	***CAS***	***DAA***
Primary Use Case	Onboard pilot	Remote pilot
Caution Alert	Traffic Advisory (TA)	Detect and Avoid (DAA)
Maneuver Guidance	Directive Resolution Advisory (RA) guidance only	Suggestive DAA guidance Directive RA Guidance
Terminal Area Behavior	TA Only mode	Vertical RAs only Smaller well clear volume
Low Altitude Behavior	Descend RAs inhibited < 750ft	Ground Point Obstacle Awareness (GPOA)

C. Simulation Environment

The present study utilized the Vertical Motion Simulator (VMS) at NASA Ames Research Center (ARC) in Mountain View, California USA. The VMS provides six degrees of freedom and generates high-fidelity out-the-window visuals, which includes terrain, obstacles, and airborne traffic [11]. The VMS utilizes an interchangeable cab capability, which allows researchers to tailor the flight deck environment to the research system(s) under test. For the current simulation, the VMS was equipped with the rotorcraft cabin, (R-cab) which replicates a single-pilot helicopter flight deck with customizable controls and displays. The R-cab provides three large windshield monitors and three large chin bubble monitors for a realistic visual flight environment (Fig. 1). Two side-stick controllers and rudders were used for control of the vehicle. The left stick commanded acceleration and deceleration and the right stick commanded vertical rate and bank angle. Deflecting the right stick also disengaged the flight plan autopilot. A thumb button on the right stick toggled a 'Hover' mode on and off.

Three separate flight deck displays were utilized. Two of the displays, the map display and the Primary Flight Display (PFD), were developed by the Aerospace Cognitive Engineering Laboratory (ACELAB) at NASA ARC and were positioned as the left-most display and center display, respectively [12]. The map display provided a top-down, satellite view of the flight region, which moved with an ownship that was centered in a track-up orientation. The map display also included range rings, a compass rose, the current flight path, and basic navigational information. The PFD provided standard information expected from this type of display (e.g., airspeed and altitude tapes, a compass rose, bank angle, and sideslip indicators) layered on top of a synthetic nose-camera view. No traffic or ACAS Xr-related information was presented within the map display or the PFD.

The last of the three displays was the ACAS Xr display, developed by the Human Autonomy Teaming (HAT) Laboratory at NASA ARC. Positioned on the right side of the flight deck, the ACAS Xr display functioned as a typical Cockpit Display of Traffic Information (CDTI), providing ownship and intruder information as well as depicting visual and aural alerting and guidance generated by ACAS Xr. Ownship information consisted of current track, altitude, airspeed, and vertical speed. Intruder information included position, direction, relative altitude, vertical trend, and alert level. The bottom half of the display included buttons for switching ACAS Xr modes (used only to switch to TA Only mode) and increasing or decreasing the range of the display.

Fig. 1. Picture of the interior of NASA Ames Research Center's Vertical Motion Simulator (VMS) rotorcraft cab.

D. Vehicle Model

The ownship and intruder aircraft dynamics were generated by a hybrid eVTOL vehicle model, referred to as the "Lift Plus Cruise" model, which was developed under NASA's Revolutionary Vertical Lift Technology (RVLT) Project [12]. Below 20 knots airspeed, the model uses thrust-borne lift and switches to semi-thrust-borne lift from 20-60 knots. From 40-90 knots, the model switches to semi-wing-borne lift, switching finally to wing-borne lift once the aircraft reaches 100 knots or greater. For detailed information regarding the model, see [12].

E. ACAS Xr

The present study leveraged the most recent ACAS Xr executable libraries that were available at the time of the test (August 2022) by the FAA TCAS Program Office. Denoted as "version 2" of ACAS Xr, the software package included the Sensor Tracker Module (STM), which ingests a variety of surveillance sensor sources to generate a single intruder track, and the Threat Resolution Module (TRM), which outputs alerting and guidance that can then be depicted within the ACAS display. No surveillance sensor models were utilized in the present experiment. As a result, ACAS Xr was operating with "perfect" surveillance data for ownship and intruders.

1) CAS Configuration

ACAS Xr's CAS configuration is designed for crewed rotorcraft operations and is intended to support pilots' ability to avoid NMACs. The CAS configuration largely reflects TCAS II's minimal alerting structure (Table 2). Traffic that was within surveillance range, but was not predicted to create a collision hazard, was depicted as "Basic" traffic. Traffic that was predicted to lead to a collision hazard, but was not yet close enough to warrant a warning-level alert, was declared a TA. The TA was a caution-level alert and included the aural annunciation "Traffic, Traffic". (Note: since version 2 of ACAS Xr was not capable of generating TAs, the TA was approximated by leveraging the Corrective DAA alert issued in the DAA configuration. As a result, TAs were issued approximately 15 seconds earlier presently than they would be with a true TA.) Pilots were not expected to maneuver in response to a TA alone during the Cruise and Hover conditions; instead, they were trained to use the traffic display to assist in visually acquiring the traffic outside of their aircraft to prepare for a potential RA maneuver. Once an RA was issued, typically around 60 seconds to closest point of approach (CPA), the traffic icon switched to a warning-level alert. Visual and aural guidance indicated the type of RA that was being commanded: a Horizontal RA (e.g., "Turn Right, Turn Right"), a Vertical RA (e.g., "Climb, Climb"), or a Blended RA (e.g., "Turn Left, Turn Left and Descend, Descend").

All RAs included directive guidance, which indicated the direction and magnitude of the commanded maneuver. For Horizontal RAs, a target track (plus a 15° buffer) was indicated by a green wedge extending from the nose of the ownship to the corresponding target track on the ACAS display range ring. A red arc overlapped the tracks on the range ring that were to be avoided. For Vertical RAs, a target vertical speed (plus a 500 feet per minute buffer) was indicated by a green band on the vertical speed tape, with a red band indicating the vertical speeds to be avoided. Both Horizontal and Vertical RA guidance was presented simultaneously during Blended RAs (see Fig. 2). Upon resolving the conflict, the RA alerting and guidance was removed from the display.

While all RA types were possible at higher altitudes in the Cruise and Hover scenarios, the alerting was modified in the CAS configuration during the Approach scenarios and when the aircraft descended below 750 feet AGL outside of the terminal area. To mimic TCAS II, pilots in the CAS configuration were trained to switch ACAS into "TA Only" mode at the start of the Approach scenarios. In doing so, RAs were suppressed entirely, and pilots could only receive Basic-level traffic or TAs. Since there is no guidance associated with TAs, maneuvering was entirely at the pilots' discretion. While in the Cruise and Hover scenarios in the CAS configuration, ACAS Xr automatically suppressed Descend RAs when the aircraft was below 750 feet AGL. This was intended to prevent the issuance of Descend RAs too close to the ground.

Fig. 2. Screenshot of the ACAS Xr traffic display during a Blended RA.

2) DAA Configuration

ACAS Xr's DAA configuration is designed primarily for remote pilots and is tuned to prevent losses of DAA well clear, in addition to NMACs. Basic traffic and RAs were presented identically between the CAS and DAA configurations. Unique to the DAA configuration alert structure was the use of Guidance traffic, Preventive DAA alerts, and Corrective DAA alerts (see Table 2). Guidance traffic indicated that another aircraft was currently responsible for DAA guidance banding that fell outside of ownship's current trajectory. Similarly, Preventive DAA alerts indicated that a piece of traffic was particularly close in altitude but not currently predicted to lose well clear. Preventive DAA alerts included the aural annunciation "Traffic, Monitor".

The last unique alert type to the DAA Configuration was the Corrective DAA alert. While the icon was identical to the TA icon in the CAS configuration, the Corrective DAA alert was paired with DAA "suggestive" guidance bands and an aural alert - "Traffic, Avoid" - that prompted pilot action. The onset of a Corrective DAA alert coincides with caution-level banding that covers the ownship's current track, airspeed, and vertical speed (see Fig. 3). The pilot's responsibility was to refer to those bands to determine if and how to maneuver. The Corrective alert was issued approximately 100 seconds prior to CPA, 40 seconds earlier than an RA.

As was the case with the CAS configuration, the DAA configuration modified its alerting in the Approach scenarios and at lower altitudes. The DAA configuration was designed to meet the terminal area requirements in [3]. This meant suppressing all DAA alerting and guidance and Horizontal RAs against intruders determined to be within the DAA terminal area, defined in [3] as within 5 nautical miles laterally and 2000 feet vertically of the arrival runway/landing pad. As a result, pilots only received Vertical RA guidance during Approach scenarios, which included guidance to either climb (i.e., execute the missed approach), descend (i.e., continue the approach), or level off.

TABLE II. ACAS XR CONFIGURATION ALERTING STRUCTURES

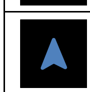
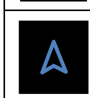
Traffic Icon	Configuration	
	CAS Alert Structure	***DAA Alert Structure***
	Resolution Advisory (RA) *"Climb/Descend" x2* *"Turn Right/Left" x2*	Resolution Advisory (RA) *"Climb/Descend" x2* *"Turn Right/Left" x2*
	Traffic Advisory (TA) *"Traffic, Traffic"*	Corrective DAA Alert *"Traffic, Avoid"*
	N/A	Preventive DAA Alert *"Traffic, Monitor"*
	N/A	Guidance Traffic *No aural alert*
	Basic	Basic *No aural alert*

Fig. 3. Screenshot of the ACAS Xr traffic display during a Corrective alert.

The DAA configuration also handled low-altitude RAs differently in Cruise and Hover than the CAS configuration. Rather than a fixed cut-off altitude of 750 feet AGL, the DAA configuration allowed pilots to descend closer to the ground by treating terrain as an intruder with a relatively smaller vertical threshold compared to the CAS configuration.

F. Procedure

1) Training

All participants spent two days at the NASA ARC VMS facility to engage in the necessary training and data collection activities. On day one, participants began by reviewing and signing an informed consent form and then filling in a demographics form. Once the demographics form was complete, the participants were provided with a slide show presentation that covered whichever ACAS Xr configuration they were going to experience first (pilots only experienced one configuration per day). The slide show began with a project overview and then moved on to cover the simulator layout, vehicle model, and simulator displays. Once completing this portion of the slide deck, the pilots received hands-on training in the simulator with motion enabled. Pilots practiced multiple maneuvers in each of the three phases of flight (Cruise, Hover, and Approach) until they demonstrated a baseline level of competence with control of the vehicle.

Once the pilots completed the first portion of the hands-on training, they resumed the slide show presentation, which transitioned into an overview of ACAS Xr and ultimately into the specific details of the ACAS Xr configuration they were to experience on day one. Once familiar with the particulars of ACAS Xr, pilots returned to the simulator to fly several practice encounters in the appropriate phase of flight. Pilots flew several practice encounters prior to each new phase of flight condition on day one. On day two, pilots began the day with a slideshow presentation that focused entirely on the remaining ACAS Xr configuration. As with day one, pilots flew several practice encounters immediately prior to each new phase of flight data collection run.

2) Experimental Trials

All experimental trials occurred in simulated Class E airspace over the San Francisco Bay Area in California under VFR. The scenarios always initialized mid-flight, with the vehicle at its mission altitude, flying in autopilot. The vehicle remained on its course until the pilot decided to take the aircraft off its course in response to ACAS Xr alerting. All maneuvers were made with the left and/or right inceptors, which immediately disengaged the autopilot in the Cruise and Approach scenarios and allowed the pilot to hand-fly the aircraft. Pilots in the Hover scenario had to take the additional step of disengaging the "Hover mode" by pressing a thumb button on the right inceptor. The conflicting aircraft all executed pre-recorded flights that were designed to lose separation with the ownship. Since they were pre-recorded, they did not maneuver in response to the ownship. No background traffic was included in the present study.

Each phase of flight condition included ten encounters that varied the ownship and intruder altitudes (500-1500 feet MSL), intruder approach angles (head-on, crossing, and converging), and intruder vertical trend (level, climbing, or descending) to generate a variety of DAA and RA alerting and guidance types. Each individual encounter lasted approximately five minutes. The encounter was considered complete once the pilots had successfully resolved the encounter and initiated a maneuver back toward their original flight plan. Pilots were trained to comply with the DAA and RA alerting generated by ACAS Xr unless they felt doing so created a safety of flight concern.

Pilots flew 30 experimental encounters (10 in each phase of flight) per ACAS Xr configuration, resulting in 60 encounters total. Pilots answered a brief questionnaire after each phase of flight and after each ACAS Xr configuration to record their feedback. After pilots had flown all encounters, they were provided with a larger questionnaire and open-ended debrief session. Pilot responses to the questionnaires and the debrief are outside the scope of this paper.

G. Metrics

ACAS Xr output logs, flight deck display screen recordings, and observer notes constituted the bulk of the data sources required to capture the objective pilot and system performance metrics of interest.

- DAA Response Times: a measure of the time elapsed (in seconds) from the onset of a Corrective DAA alert and the initiation of the corresponding avoidance maneuver. Only captured in the DAA configuration in the Cruise and Hover scenarios.
- TA Response Times: a measure of the time elapsed (in seconds) from the onset of a Traffic Advisory and the initiation of the corresponding avoidance maneuver. Only captured in the CAS configuration in the Approach scenario.
- RA Response Times: a measure of the time elapsed (in seconds) from the onset of an initial Horizontal or Vertical RA and the initiation of the corresponding avoidance maneuver. Captured in all phases of flight and configurations except the CAS configuration in the Approach scenario.
- RA Breakdown: percentage of encounters with Horizontal RAs (single-axis), Vertical RAs (single-axis), and Blended RAs (multi-axis) per flight phase and ACAS Xr configuration. Captured in all phases of flight and configurations except the CAS configuration in the Approach scenario.
- En-Route Losses of DAA Well Clear: proportion of encounters that resulted in an en-route loss of DAA well clear. Only captured in the Cruise and Hover scenarios. (Refer to Table 3 for all loss of separation definitions.)
- High-Severity Losses of DAA Well Clear: proportion of encounters that resulted in a high-severity loss of DAA well clear. Only captured in the Cruise and Hover scenarios.
- Terminal Area Losses of DAA Well Clear: proportion of encounters that resulted in a terminal area loss of DAA well clear. Only captured in Approach scenarios.
- NMACs: proportion of encounters that resulted in an NMAC. Captured in all configurations and scenarios.
- RA Non-Compliance: proportion of RA encounters where the pilot refused to fully comply with the RA(s). Non-compliance only captured cases where pilots intentionally neglected or disregarded an RA (e.g., pilot maneuvered in opposite dimension or direction than the commanded RA, pilot ceased their RA maneuver before the RA conflict had cleared). Captured in all phases of flight and configurations except the CAS configuration in the Approach scenario.

III. Results

The present paper reports on pilot and system performance while utilizing ACAS Xr in a full-motion simulator across two ACAS Xr configurations (CAS and DAA) and three phases of flight (Cruise, Hover, and Approach). Due to the extensive differences between the flight phases, the results below are organized by phase of flight, with two-sided dependent samples t-tests only performed on the ACAS Xr configuration variable where practical. Descriptive statistics are provided for all metrics.

TABLE III. LOSS OF SEPARATION DEFINITIONS

	Separation Criteria		
Loss of Separation Type	***Horizontal Threshold***	***Vertical Threshold***	***Modified Tau***[a]
En-Route DAA Well Clear	4000 feet	450 feet	35 seconds
High-Severity DAA Well Clear	4000 feet	450 feet	N/A
Terminal Area DAA Well Clear	1500 feet	450 feet	N/A
Near Midair Collision	500 feet	100 feet	N/A

[a.] Modified Tau (modTau) is approximately equivalent to time to closest point of approach.

A. Cruise Scenarios

1) DAA Response Times

DAA response times averaged 5.24 seconds (*SE* = 1.02s).

2) RA Response Times

No significant effect was found for the ACAS Xr configuration variable on RA response times to the initial Horizontal RA issued in an encounter (DAA: M = 1.13s, SE = 0.72s; CAS: M = 1.83s, SE = 0.20s), $t(3) = -1.13$, $p > 0.1$ (see Fig. 4). A significant effect of ACAS Xr configuration was found, however, on response times to the initial Vertical RA issued in an encounter (DAA: M = 1.23s, SE = 0.27s; CAS: M = 2.85s, SE = 0.34s), $t(4) = -2.84$, $p = 0.047$.

3) RA Breakdown

The types of RAs that occurred in the Cruise scenario in the DAA and CAS configurations are shown in Table 4. Only 32% of encounters in the DAA configuration progressed to an RA (the remainder were resolved as part of the pilot's response to the Corrective DAA alert). Single-axis Vertical RAs were the most common type of RA in both configurations in Cruise.

4) En-Route Losses of DAA Well Clear

A significant effect of ACAS Xr configuration was found on the average proportion of encounters that resulted in an en-route loss of DAA well clear, with significantly more losses occurring in the CAS configuration (M = 0.25, SE = 0.02) than in the DAA configuration (M = 0.06, SE = 0.06), $t(5) = -2.84$, $p = 0.036$ (see Fig. 5).

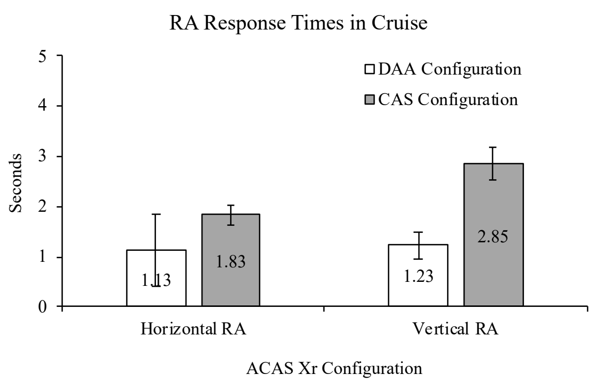


Fig. 4. Average RA response times in the Cruise phase of flight, by RA type and ACAS Xr configuration.

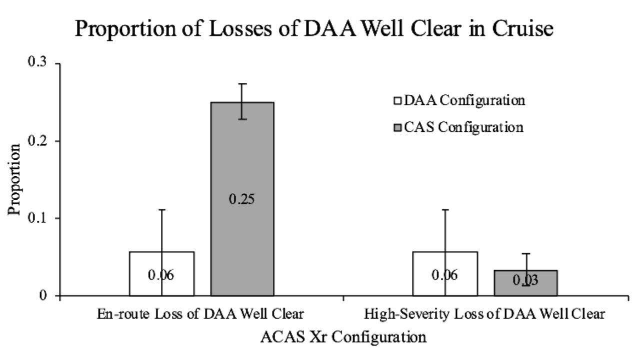


Fig. 5. Average proportion of en-route and high-severity losses of DAA well clear in the Cruise phase of flight, by ACAS Xr configuration.

5) High-Severity Losses of DAA Well Clear

No significant effect of ACAS Xr configuration was found on the average proportion of encounters that resulted in a high-severity loss of DAA well clear, $t(5) = 0.34$, $p > 0.01$. In both conditions, the number of high-severity losses of DAA well clear was low (DAA: M = 0.06, SE = 0.06; CAS: M = 0.03, SE = 0.02;) (see Fig. 5).

6) Near Midair Collisions

No NMACs were recorded in either ACAS Xr configuration across the Cruise scenarios.

7) RA Non-Compliance

No significant effect of ACAS Xr configuration was found on the average proportion of RAs that pilots did not comply with while in Cruise (DAA: M = 0.11, SE = 0.07; CAS: M = 0.18, SE = 0.07), $t(5) = -0.56$, $p > 0.1$. Non-compliance while in Cruise in the CAS configuration was primarily due to pilots disregarding a Level-Off RA in order to actively climb or descend against an intruder. Non-compliance in the DAA configuration included one case of (apparent) pilot error and one case where the pilot disregarded an RA because it was issued as the ownship and the intruding aircraft were diverging.

B. Hover Scenarios

1) DAA Response Times

DAA response times averaged 7.18 seconds (*SE* = 1.04s).

2) RA Response Times

No significant effect was found for the ACAS Xr configuration variable on RA response times to the initial Horizontal RA issued in an encounter (DAA: M = 3.13s, SE = 0.97s; CAS: M = 4.06s, SE = 0.42s), $t(3) = 1.57$, $p > 0.1$ (see Fig. 6). ACAS Xr configuration also failed to have a significant effect on pilot response times to the initial Vertical RA (DAA: M = 2.75s, SE = 0.48s; CAS: M = 6.07s, SE = 1.61s), $t(5) = -1.28$, $p > 0.1$.

3) RA Breakdown

The types of RAs that occurred in the Hover scenario in the DAA and CAS configurations are shown in Table 4. In the DAA configuration, 60% of encounters progressed to an RA. Single-axis Vertical RAs were the most common type of RA in both configurations in Hover.

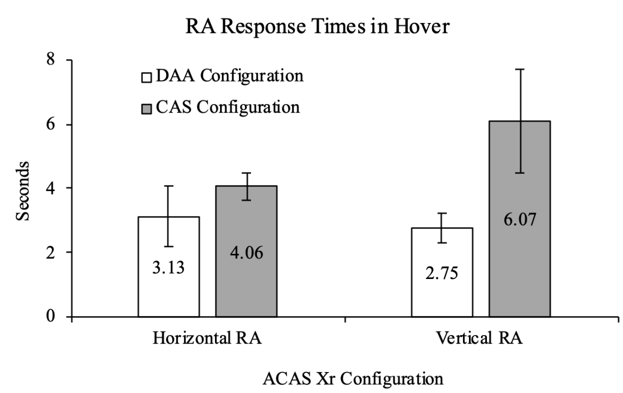


Fig. 6. Average RA response times in the Hover phase of flight, by RA type and ACAS Xr configuration.

TABLE IV. PERCENTAGE OF ENCOUNTERS WITH GIVEN RA TYPES

RA Type	Cruise		Hover	
	DAA Config.	***CAS Config.***	***DAA Config.***	***CAS Config.***
Horizontal (single-axis)	3%	28%	0%	8%
Vertical (single-axis)	22%	48%	45%	80%
Blended (multi-axis)	7%	23%	15%	12%
Total % of Encounters	*32%*	*100%*	*60%*	*100%*

4) En-Route Losses of DAA Well Clear

ACAS Xr configuration had a significant effect on the average proportion of encounters that resulted in an en-route loss of DAA well clear in Hover (DAA: $M = 0.38$, $SE = 0.1$; CAS: $M = 0.67$, $SE = 0.03$), $t(5) = -3.48$, $p = 0.018$ (see Fig. 7).

5) High-Severity Losses of DAA Well Clear

ACAS Xr configuration was also found to have a significant effect on the average proportion of encounters that resulted in a high-severity loss of DAA well clear (DAA: $M = 0.13$, $SE = 0.04$; CAS: $M = 0.25$, $SE = 0.03$), $t(5) = -2.57$, $p = 0.049$ (see Fig. 7).

6) Near Midair Collisions

No NMACs were recorded in either ACAS Xr Configuration in Hover.

7) RA Non-Compliance

ACAS Xr configuration was found to have a significant effect on the average rate of RA non-compliance in the Hover scenarios (DAA: $M = 0.46$, $SE = 0.08$; CAS: $M = 0.13$, $SE = 0.04$), $t(5) = 6.83$, $p = 0.001$. All of the instances of RA non-compliance in the DAA configuration resulted from pilots leveling-out or climbing while a Descend RA was still active due to terrain proximity. Just under half of the instances of non-compliance in the CAS configuration were due to pilots preferring a climb or descent over a Level-Off RA. The remainder saw pilots level out of a Climb RA early and execute a climb rather than a Horizontal RA.

C. Approach Scenarios

1) TA Response Times

Pilot response times to Traffic Advisories while flying the Approach scenarios in the CAS Configuration averaged 22.88 seconds ($SE = 7.07$s).

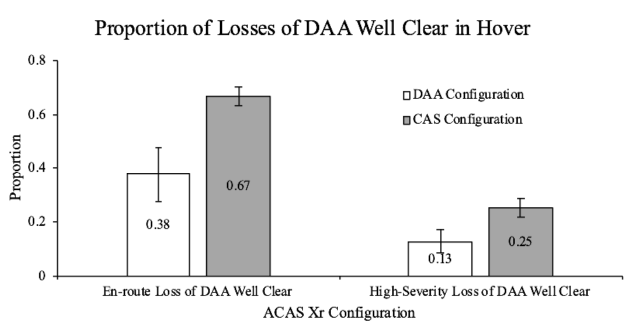


Fig. 7. Average proportion of en-route and high-severity losses of DAA well clear in the Hover phase of flight, by ACAS Xr configuration.

2) RA Response Times

During the Approach scenarios, RAs were limited to the DAA configuration and were only issued in the vertical dimension. Average pilot response times to Vertical RAs on Approach were 2.64 seconds ($SE = 0.25$s).

3) RA Breakdown

Only Vertical RAs were permitted in the Approach scenario.

4) Terminal-Area Losses of DAA Well Clear

ACAS Xr configuration did not have a significant effect on the average proportion of encounters that resulted in a terminal area loss of well clear (DAA: $M = 0.22$, $SE = 0.05$; CAS: $M = 0.30$, $SE = 0.12$), $t(5) = -0.70$, $p > 0.1$.

5) Near Midair Collisions

Unlike the Cruise and Hover scenarios, NMACs were observed in the Approach scenarios. ACAS Xr configuration was not, however, found to have a significant effect on the average proportion of encounters that resulted in an NMAC, with each condition experiencing two NMACs across all pilots (DAA: $M = 0.03$, $SE = 0.02$; CAS: $M = 0.03$, $SE = 0.02$), $t(5) = 0.0$, $p > 0.1$.

6) RA Non-Compliance

Since no RAs were issued in the CAS configuration during the Approach scenarios, RA non-compliance was only possible in the DAA configuration. Pilots were found to not fully comply with Vertical RAs at a rate of 0.18 ($SE = 0.11$). The reason for the non-compliance, in 82% of cases, was the pilot deciding to climb or descend during a Level-Off RA.

IV. DISCUSSION & CONCLUSION

A. Effect of ACAS Xr Configuration

The current study assessed pilots' utilization of ACAS Xr under two different configurations and across three distinct phases of flight. Our findings suggest that, within a given phase of flight, the ACAS Xr configuration had the most pronounced effect on the likelihood of pilots losing DAA well clear. It is by no means surprising that the DAA configuration outperformed the CAS configuration on this metric in both the Cruise and Hover scenarios, since the CAS configuration is designed specifically to prevent near midair collisions, not losses of DAA well clear. A positive follow-on effect of avoiding more losses of DAA well clear was a reduction in the number of RAs issued when in the DAA configuration. The DAA configuration avoided 70% of RAs in Cruise scenarios and 40% of RAs in Hover scenarios. It should be noted that the rate of en-route losses of DAA well clear was only 0.25 in the CAS configuration in Cruise (compared to 0.06 for the DAA configuration). In other words, with RAs alone, ACAS Xr was found to prevent 75% of en-route losses of DAA well clear. The rate of high-severity losses of DAA well clear was even lower for the CAS configuration in Cruise, dropping to 0.06. Crucially, no NMACs were recorded in either the DAA or the CAS configuration in Cruise or in Hover, suggesting that both configurations can reliably avoid the midair collision boundary.

ACAS Xr's CAS configuration was also found to result in significantly slower pilot response times to Vertical RAs in Cruise and significantly fewer instances of RA non-compliance while in Hover, compared to the DAA configuration. While the impact on Vertical RA response times was statistically significant, the difference between the two configurations was only 1.6 seconds. Furthermore, the response time still fell within ACAS Xr's 5-second response time assumption, which lessens the practical impact of the difference. The difference between the two configurations on RA non-compliance, however, was far more pronounced. Pilots were more than three times as likely to not comply with a given RA in the DAA configuration than in the CAS configuration while flying in the Hover scenarios. The difference was driven entirely by the issuance of more Descend RAs in the DAA configuration that directed the pilots to fly closer to the ground than in the CAS configuration. Pilots consistently leveled-out or climbed while a Descend RA was still active in the DAA configuration in Hover, whereas there were no such cases in the CAS configuration.

B. Trends Between Phases of Flight

While the results focused on the ACAS Xr configuration comparisons within each phase of flight, it is equally useful to contrast pilot and system performance across flight phases. Pilot response times to DAA alerts differed by only 2 seconds across the Cruise and Hover scenarios (DAA alerts were not issued in Approach scenarios). Surprisingly, however, the DAA response times in this study were nearly as fast as the RA response times. While RAs are issued with directive guidance, DAA alerting is accompanied by suggestive guidance. Despite the need to assess the suggestive banding and decide on a course of action, pilots took only 3-4 seconds longer, on average, to initiate their avoidance maneuver in response to a DAA alert than to an RA. These especially fast DAA response times are consistent with the response times observed in an earlier ACAS Xr study but are 10 seconds faster than those found in prior studies with ACAS Xu (the large UAS variant of ACAS X) [7-10]. The faster times with ACAS Xr can be explained by the fact that the pilot was onboard the aircraft, maneuvering with side-stick controllers rather than the mouse and keyboard inputs made by pilots interacting with ACAS Xu at a ground control station. The ACAS Xu pilots were also operating under IFR, which meant that they needed to receive approval from Air Traffic Control (ATC) before they could execute a DAA maneuver. These findings suggest that the use of a DAA system in an onboard pilot configuration will likely lead to maneuvers that start earlier than is expected of UAS DAA systems.

As was seen with DAA response times, pilot response times to RAs were consistent across all three scenarios, with pilots meeting the 5-second response time assumption in all cases except in response to Vertical RAs in the Hover scenario, where the average was 6 seconds. This slightly slower response time was likely due to the added requirement in Hover scenarios for pilots to disengage the Hover mode. While pilots had to disengage Hover mode when responding to Horizontal RAs and Vertical RAs alike, pilots' general tendency to respond to Vertical RAs slightly more slowly than to Horizontal RAs meant that only Vertical RA response times in the Hover scenario exceeded the 5-second threshold.

The types of RAs issued, rates of losses of separation, and rates of RA non-compliance all varied considerably between phases of flight. In the present study, Vertical RAs were the most common type of RA issued in all flight phases. Vertical RAs were particularly common in the Hover scenarios, where they were issued at approximately twice the rate of Vertical RAs in the Cruise scenarios. In the CAS configuration, for instance, single-axis Vertical RAs made up 80% of encounters in Hover, compared to 48% in Cruise. The prevalence of Vertical RAs was partly due to experimental design choices (e.g., several encounters in Cruise and in Hover were intended to generate Descend RAs and RAs in the Approach scenario were limited to the vertical dimension), but the increase between these flight phases may suggest a bias toward vertical advisories in low-speed encounters. Such a bias could have consequences for pilot compliance rates, especially if it leads to a greater number of Descend RAs close to the ground, which is discussed below.

The rate of en-route and high-severity losses of DAA well clear were far higher for both ACAS Xr configurations in Hover scenarios than was observed in Cruise. The rate of en-route losses of DAA well clear in the DAA configuration was more than six times higher in Hover than in Cruise, while the rate of high-severity losses of DAA well clear doubled from Cruise to Hover. As has been established, DAA response times in the present study were especially fast in the Cruise and Hover scenarios compared to DAA response times that have been collected previously with remote pilots. One should therefore expect the rate of losses of DAA well clear in Hover to be even higher when used in the context of UAS with remote pilots. This strongly suggests that ACAS Xr does not properly account for the time required for the vehicle to exit out of a hover. By not affording the vehicle additional time to accelerate and then begin a horizontal or vertical maneuver, the rates and severity of losses of DAA well clear will be substantially higher than the rates observed while in forward flight. The lack of accounting for vehicle response times in Hover was also reflected in the greater number of RAs that were issued in the DAA configuration during Hover scenarios. In Cruise, 32% of encounters with the DAA configuration resulted in an RA, compared to 60% of encounters in Hover.

While the alerting and guidance logic was identical between Cruise and Hover scenarios, the schema differed significantly during Approach scenarios. All RAs were suppressed on Approach in the CAS configuration, whereas all DAA alerts and Horizontal RAs were suppressed in the DAA configuration. Unlike the Cruise and Hover scenarios, ACAS Xr configuration did not have a significant effect on the rate of losses of DAA well clear during approaches. Not only were the rates of terminal area DAA well clear violations similar, but both conditions experienced two NMACs, an indication that ACAS Xr may not be adequately tuned to terminal area operations. In the case of the CAS configuration, terminal area losses of DAA well clear often occurred because pilots took too long to maneuver, or failed to maneuver at all, since they were maneuvering off of TAs alone, which had no accompanying guidance. Pilot response times to TAs averaged

23 seconds, much longer than DAA response times, which averaged less than 8 seconds in Cruise and Hover scenarios. This highlights the inherent risk in switching to TA-Only mode in the terminal environment, which removes potentially useful information regarding the severity of a given conflict. The DAA configuration, conversely, issued Vertical RAs in the terminal area, but often failed to successfully resolve the conflict. The primary factor that led to terminal area losses of DAA well clear, NMACs, and instances of pilot non-compliance in the DAA configuration were the issuance of Level-Off RAs on Approach. Unlike Climb RAs in this condition, Level-Off RAs failed to generate sufficient vertical distance between the ownship and the intruder at closest point of approach, which resulted in losses of separation and cases where pilots chose to actively contradict the guidance issued by ACAS Xr.

Lastly, the rate of RA non-compliance was also observed to vary greatly between phases of flight. The average rate of non-compliance ranged from 0.11 to 0.18 across the Cruise and Approach scenarios. While the rate of RA non-compliance also fell within that range in the Hover scenarios for the CAS configuration, the DAA configuration more than doubled the second-highest rate of non-compliance, with an average rate of 0.46 in Hover scenarios. The combination of the DAA configuration's GPOA feature and the high rate of Vertical RAs issued in the Hover scenarios resulted in pilots experiencing a greater number of Descend RAs that remained active close to the ground. This led to a corresponding increase in the number of pilots that reversed ACAS Xr's guidance to either level-off or climb when a Descend RA was commanded.

Taken together, the results presented in this paper demonstrated clear effects of flight phase and ACAS Xr configuration. The results of the ACAS Xr configuration variable were consistent with expectations; namely, that the DAA configuration is much more likely to maintain DAA well clear and prevent RAs from occurring in the first place when flying in Cruise and in Hover. The introduction of the phase of flight variable also revealed important limitations of the current version of ACAS Xr. While the rate of losses of DAA well clear in Cruise was consistent with what was observed in previous research with ACAS Xu and ACAS Xr, the rates of losses of well clear in the DAA configuration increased substantially in Hover and Approach scenarios in the present study [7-10]. Rates of RA non-compliance were also found to increase considerably in Hover scenarios. These findings lead to several recommendations that should lead to improved pilot and system performance in these new phases of flight for ACAS Xr. First, the logic should account for the time required for rotorcraft to exit a hover in response to DAA and RA alerting to reduce the rates and severity of losses of separation. Second, the Ground Point Obstacle Awareness feature should be calibrated to pilot comfort levels to reduce the likelihood of pilots disregarding RAs while operating near the ground. Third, ACAS Xr's DAA terminal area logic should remove Level-Off RAs to prevent severe losses of separation and to promote pilot compliance with RAs.

C. *Study Limitations*

The current study focused on an early iteration of ACAS Xr. Future versions are planned to be released that will likely address many of the issues raised in this paper. Furthermore, the use of "perfect" surveillance data may have impacted the types and timing of the RAs issued presently, since ACAS Xr was developed and tuned to representative sensor performance. The lack of background traffic may have also distorted pilots' perceptions of the CAS and DAA configurations since they did not need to take other aircraft or traffic flows into consideration when deciding if, and how, to maneuver.

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REFERENCES

[1] Federal Aviation Administration, "Urban Air Mobility, Concept of Operations, v2.0," 2023.

[2] U.S. General Accounting Office, Title 14 – Aeronautics and space, Chapter I – Federal Aviation Administration, Department of Transportation Part 91 General operating and flight rules, retrieved from GovInfo Online via https://www.govinfo.gov/content/pkg/CFR-2020-title14-vol2/pdf/CFR-2020-title14-vol2-part91.pdf, 2020.

[3] RTCA, "Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems Revision B," (No. DO-365B). Washington, DC: RTCA 2020.

[4] RTCA, "Minimum Operational Performance Standards (MOPS) for Airborne Collision Avoidance System Xu," (No. DO-386, Vol. 1). Washington, DC: RTCA 2020.

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

[6] RTCA, "Minimum Operational Performance Standards (MOPS) for Airborne Collision Avoidance System for Rotorcraft (Xr)," Washington, DC: RTCA, unpublished.

[7] Sadler, G., Rorie, R.C., Smith, C.L, Keeler, J.N., and Monk, K. J., "Display and Automation Considerations for the Airborne Collision Avoidance System Xu," *AIAA AVIATION 2020 Forum*, Reno, NV, 2020.

[8] 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.

[9] 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 X_U," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 64, No. 1, 2020, pp. 159–163.

[10] Smith, C. L., Rorie, R. C., Chandarana, M., Tyson, T. L., and Keeler, J., "Helicopter Pilot Assessments of the Airborne Collision Avoidance System X_R with Automated Maneuvering," *AIAA AVIATION 2023 Forum*, San Diego, CA, 2023.

[11] 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.

[12] 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.