

Human-in-the-Loop Flight Simulation Experiment on Unmanned Aircraft Terminal Operations

Devin P. Jack¹ and Keith D. Hoffler²

Adaptive Aerospace Group, Hampton, VA, 23663

Roy D. Roper³, Anna C. Trujillo⁴, E. Tod Lewis⁵, and Sagar KC⁶

National Aeronautics and Space Administration, Hampton, VA, 23681

Dimitrios Tsakpinis⁷

SAIC, Hampton, VA, 23681

A Detect and Avoid (DAA) System is a suite of sensors, tracker, and alerting and guidance algorithms that assist a remote pilot of an Unmanned Aircraft System in maintaining separation from airborne traffic by complying with current ‘see and avoid’ requirements. To date, work has focused on operations transiting to and from Class A or special use airspace. Current efforts are defining DAA system requirements for operations in and around terminal airspace. As a contribution to the current efforts, this paper presents results from a Human-in-the-Loop experiment comparing methods of changing from the transit-specific alerting and guidance criteria to the reduced terminal-specific alerting and guidance criteria.

I. Introduction

Detect and Avoid (DAA) is an essential component of integrating Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS). All aircraft operating in the National Airspace System (NAS) are required to see and avoid other aircraft when weather conditions permit, whether operating under Instrument Flight Rules (IFR) or Visual Flight Rules (VFR), per Title 14 of the Code of Federal Regulations (14 CFR) 91.113 [1]. The recently published RTCA DO-365, Minimum Operational Performance Standards (MOPS) for DAA Systems, provides the requirements for a DAA system that enables unmanned aircraft (UA) to meet the see and avoid requirement under limited conditions.

To date, RTCA DO-365 development has focused on UA operations transitioning to and from Class A and Special Use Airspace and provides a DAA Well Clear (DWC) definition and alert times appropriate for the higher speed conflicts that may occur in that airspace [2]. The Terms of Reference (TOR) for SC-228, the guiding document for the committee, indicates the next publication of the MOPS will focus on two goals: enabling operations for smaller UAS and enabling a broader range of operating environments including towered and non-towered terminal airspace. The Terminal Operations 2 (TOPS2) human-in-the-loop (HITL) simulation discussed herein was part of the latter goal and focused on the alerting performance in and around the airport traffic patterns.

NASA has completed a series of fast-time and HITL simulations focused on UA operations around the terminal environment. A fast-time simulation [3] demonstrated that the En Route DWC definition and associated alerting scheme is too large for conflicts with aircraft within or entering the Visual Flight Rules (VFR) traffic pattern, and the TOPS1 HITL experiment confirmed that the alerting was not acceptable to subject pilots [4]. A second HITL

¹ Research and Development Engineer, AIAA Member.

² President, AIAA Associate Fellow.

³ Research Aerospace Engineer, Crew Systems and Aviation Operations Branch.

⁴ Senior Research Engineer, Crew Systems and Aviation Operations Branch, AIAA Member.

⁵ Research Engineer, Crew Systems and Aviation Operations Branch.

⁶ Research Engineer, Crew Systems and Aviation Operations Branch.

⁷ Research and Development Engineer.

experiment, TOPS1B, evaluated two proposed DWC definitions for use in the terminal area with a 30s warning alert time [5]. TOPS1B selected a Terminal DWC and, for the conflict geometries used in the experiment, determined only alerts preceding imminent losses of DWC are needed for safe terminal operations.

As a continuation of this research, researchers at NASA Langley Research Center have completed the Terminal Operations 2 (TOPS2) HITL experiment. The objective for TOPS2 was to provide recommendations for the appropriate spatial or temporal switch from the En Route DWC to Terminal DWC in the local airport environment using the previously derived DWC parameters.

A. Terminal Operations

Terminal operations consist of operations closely associated with the landing and take-off phases of flight including the approach to and the departure from the immediate airport vicinity. In visual meteorological conditions (VMC), it is generally recommended for manned aircraft to fly the visual traffic pattern as the aircraft approaches the destination airport. The visual traffic pattern, shown in Fig. 1, consists of the following legs: entry, downwind, base, final, departure, and crosswind.

For operations in instrument meteorological conditions (IMC), there are published instrument approach procedures (IAP). The IAPs are specifically designed per airport and define a volume around the approach corridor that protects the aircraft from known terrain and obstacles. If a deviation from the IAP is needed to maintain safety of flight, pilots follow the published Missed Approach Procedure (MAP) which generally consists of a maneuver in the positive vertical dimension to remain within the protected approach corridor. Beyond the published approach procedures, in IMC conditions, air traffic control provides separation services.

As indicated in the current TOR, the UA must fly published, straight-in IAPs even in VMC conditions. A consequence of this operational assumption is the UA will fly the instrument approach while manned aircraft are flying the visual pattern. The DAA system, as it functions in the approach and landing phase, should allow the approach to proceed under nominal aircraft separations that a manned aircraft would accept. Typical piston aircraft flying the downwind leg of the traffic pattern will regularly generate alerts; when these alerts reach warning-level, the UA pilots are trained to immediately start an avoidance maneuver. An aircraft is not allowed to turn off the approach course when flying an instrument approach which would mean the UA must initiate a missed approach. Given the approach path is approximately 10 nmi, executing a missed approach means the UA must fly a minimum of 20 nmi to reestablish the approach and fly it to touchdown. Alerts from the En Route DAA system would occur against most piston aircraft flying the Visual Flight Rules (VFR) traffic pattern making it very difficult for a UA to operate at an airport with manned aircraft. Due to these shortcomings, a Terminal DWC has been proposed by SC-228.

B. DAA Well-Clear Definition

Per 14 CFR 91.113 [1], “vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft. When a rule of this section gives another aircraft the right-of-way, the pilot shall give way to that aircraft and may not pass over, under, or ahead of it unless well clear”. Thus, utilizing an onboard pilot’s ability to see and avoid traffic, an aircraft must remain ‘well clear’ from other vehicles at all times. With a pilot onboard, the definition of well clear is qualitative, based on the ability, judgment, and preferences of the pilot in command. A quantitative definition of well clear is required to establish separation requirements for unmanned aircraft DAA systems. A quantitative definition of well clear provides a repeatable target for which a DAA system may support safe separation from other aircraft by providing information to the pilot or to automation. The DAA Well Clear volume is intended to include interoperability principles with respect to Air Traffic Control (ATC) operations and current collision avoidance systems such as the Traffic alert and Collision Avoidance System (TCAS). To ensure interoperability with the current NAS, values used to define the well-clear volume must be large enough to avoid issuance of TCAS corrective resolution advisories but not so large as to interfere with ATC separation services [6]. This definition has been discussed and refined through a process involving NASA, Department of Defense (DoD), Federal Aviation Administration (FAA), and RTCA SC-228.

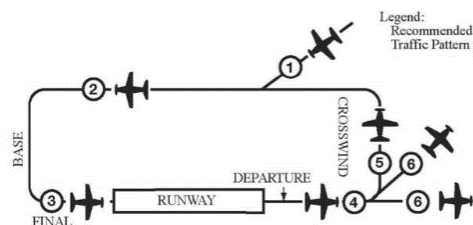


Fig. 1 VFR Traffic pattern [7]

The definition of a DAA Well Clear volume is represented using the following inequality:

$$[0 \leq \tau_{mod} \leq \tau_{mod}^* . and . HMD \leq HMD^*] . and . [-h^* \leq dh \leq h^*] \quad (1)$$

where HMD is the kinematic projection of minimum horizontal miss distance in feet, and dh is the vertical separation between the two aircraft involved in the encounter. In Eqs. 1 through 4, the lack of a superscript denotes the instantaneous value at any given time during the encounter. The superscript * denotes the value given as a minimum in the quantitative definition of well clear. Table 1 shows the numeric values used to define the DAA Well Clear threshold.

The definition of modified tau, τ_{mod} , is inherited from TCAS [8] and given in seconds by

$$\tau_{mod} = \frac{DMOD^2 - r^2}{\dot{r}r} \quad (2)$$

where TCAS defines DMOD as a horizontal distance threshold with varying values depending on the ownship's altitude, range (r), and range rate ($\dot{r}$) between the two aircraft. For the purposes of the DAA Well Clear definition, the HMD* is used in place of DMOD. The predicted horizontal miss distance is represented as:

$$HMD = \sqrt{(d_x + v_{rx}t_{CPA})^2 + (d_y + v_{ry}t_{CPA})^2} \quad (3)$$

where d_x is the horizontal separation in the x-dimension, d_y is the horizontal separation in the y-dimension, v_{rx} is the relative horizontal velocity in the x-dimension, and v_{ry} is the relative horizontal velocity in the y-dimension. The parameter t_{CPA} is the time to closest point of approach (CPA) and is calculated as:

$$t_{CPA} = \max\left(0, -\frac{d_x v_{rx} + d_y v_{ry}}{v_{rx}^2 + v_{ry}^2}\right) \quad (4)$$

Table 1 DAA Well Clear parameters.

Parameter	Symbol	Units	Values	
			En Route DWC	Terminal DWC
Vertical Displacement	h^*	feet	450	450
Modified Tau	τ_{mod}^*	seconds	35	0
Horizontal Miss Distance	HMD*	feet	4000	1500

Since En Route DWC parameters are large enough to create nuisance alerts in and near the traffic pattern, smaller parameters were desired for testing the Terminal DWC. The definition for Terminal DWC alerting used in this study, listed in Table 1, is used to minimize alerts from aircraft on the VFR downwind leg <4000 ft. offset from the runway centerline and slow moving traffic on the 45-degree entry to the VFR pattern. The alerting values were derived from the TOPS1B HITL conducted at Ames Research Center. To reduce the potential of distracting, non-essential alerts during the landing phase of flight, only the Warning alert was used with the Terminal DWC definition, based on the recommendation of RTCA SC-228.

C. DAA System Overview

A DAA system is a suite of sensors, tracker, and alerting and guidance algorithms that assist a remote pilot in maintaining DWC from airborne traffic. A series of alerting requirements are presented in DO-365 to provide the remote pilot sufficient time and awareness to maintain DWC. The alerting requirements introduce a series of hazard zones (HAZ) which define the alerting volumes for each DWC definition. For the En Route DWC definition, the

alerting scheme consists of three increasing alert levels: Preventive, Corrective, and Warning. The Corrective and Warning alerts are designed to protect the DWC volume. The Corrective alert is a caution-level provides sufficient time for the remote pilot to coordinate with ATC or the intruder aircraft to determine the appropriate maneuver, while the Warning alert is more urgent, providing only enough time for the remote pilot to maneuver to maintain DWC. The Preventive alert is also a caution-level alert and is designed to prevent vertical maneuvers that would cause rapid incursions of the DWC volume. The Preventive and Corrective alerts are unique to the En Route DWC; that is, the Terminal DWC is associated with only a Warning alert. Table 2 shows the HAZ volumes and alerting times used in this experiment.

Table 2 DWC Alerting Schemes

DWC Alerting Criteria			Preventive Alert	Corrective Alert	Warning Alert
En Route DWC	Hazard Zone (HAZ)	τ_{mod}^* (sec.)	35	35	35
		HMD^* (nmi.)	1	1	1
		h^* (ft.)	750	450	450
	Alert (sec before HAZ)		60	60	30
Terminal DWC	Hazard Zone (HAZ)	τ_{mod}^* (sec.)	N/A	N/A	0
		HMD^* (ft.)			1500
		h^* (ft.)			450
	Alert (sec before HAZ)				30

NASA Langley Research Center has developed a representative DAA alerting and guidance algorithm, DAIDALUS, to assist UA pilots in their responsibility to remain well clear of other aircraft. DAIDALUS is designed to determine whether the UA will enter the defined DAA Well Clear (DWC) volume surrounding an intruder aircraft and provide alerts to that fact, as well as lateral and vertical maneuver guidance to avoid entering the volume.

Both intruder aircraft with broadcast state data and those whose state data must be determined by sensors onboard the ownship or on the ground are taken into account by DAA guidance. In the DAIDALUS reference implementation, headings are probed at 1° increments and provide 360° coverage, while altitudes are probed at 100 ft. increments within ± 2000 ft. of the ownship vehicle [9]. The underlying software develops a hazard zone (HAZ) alert volume based on the state data of the conflicting vehicles (i.e., speed, altitude, heading, etc.) projected along 4D tracks (Fig. 2).

When intruder aircraft trajectories project into the HAZ volume, a *conflict* arises and an alert is issued to the UA operator in advance of a HAZ violation. Specifically, scripted aural alerts and displayed icons on a moving map display notify the subject to a DWC intruder (i.e., a trajectory conflict) (Table 3). Icons indicating higher conflict severity levels appear in yellow associated with the Preventive and Corrective alerts and in red for Warning alerts.

DAA alerts provides notification to the subject of an impending conflict and is based on the straight-line projections of both the ownship and intruder's speed and attitude. In addition to conflict alerts, DAA maneuver guidance is provided to aid the remote pilot in decision making to remain DAA well clear. Corrective and warning maneuver guidance are displayed on the compass rose and either the vertical speed or altitude tapes. The guidance informs the remote pilot of headings and vertical speeds or altitudes that, if flown, would lead to a loss of DAA well clear within a specified look-ahead time. Fig. **Error! Reference source not found.** shows an evolution of the heading guidance during an encounter

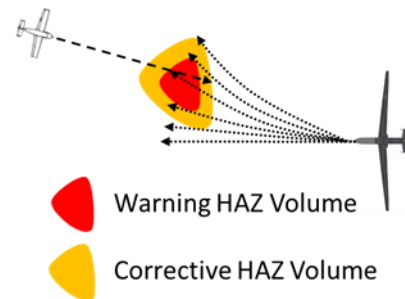


Fig. 2 Hazard alert volumes.

between a UA and intruder aircraft. In Fig. 3a, no loss of DAA well clear is predicted within the specified look-ahead time. In Fig. 3b, a corrective alert and associated guidance has been provided, indicating that a loss of DAA well clear will occur between 30 and 60 seconds in the future. The corrective alert allows time for the pilot to coordinate with ATC prior to maneuvering. In Fig. 3c, a warning alert and associated guidance has been provided, indicating that a loss of DAA well clear will occur within 30 seconds. A maneuver is expected to be executed immediately, followed by coordination with ATC. If a loss of DAA well clear occurs or is unavoidable, warning maneuver guidance is provided for all headings indicating that there are no available headings to remain well clear. A saturated compass rose also indicates the urgency of the situation to the remote pilot. In this event, Fig. 3d shows recovery guidance, which provides expedient headings to regain DAA well clear. For TOPS2, similarly behaved maneuver guidance was also implemented on the altitude tape.

D. DAA Terminal Area

The introduction of an additional DWC definition necessitates the determination of when and to whom each DWC definition applies. The DTA is the predefined region around a runway in which the Terminal DWC definition is applied to account for the reduced separation between aircraft arriving and departing the active runway. Per the Concept of Operations for UAS Operations in the Terminal Area [10], the DTA will define which traffic will have the Terminal DWC and alerting definition applied. Vehicles near the runway are likely to reduce speed when inbound to the runway, transitioning from the cruise to landing phase of flight, or conversely, increase speed when outbound from the runway, transitioning from the departure to cruise phase of flight. Determining when or where to switch between En Route and Terminal DWC operations is non-trivial because aircraft operational needs change based on speed. Two vehicles moving at fast speeds are alerted to a conflict at larger distances from each other than slow moving vehicles. Further, a faster vehicle is more likely to fly a larger traffic pattern with a long vector projection, while a slower vehicle will be the opposite.

The DTA variations tested during this HITL experiment are further described in Section III.

Table 3. DWC icons and aural alerts.

Symbol	Name	Pilot Action	Aural Alert Verbiage
	Traffic	Traffic within sensor range	N/A
	Proximate Traffic	Traffic generating guidance bands outside of current course	N/A
	Preventive Alert	Not currently a threat; monitor for potential increase in threat level	"Traffic, Monitor"
	Corrective Alert	Coordinate with ATC or other traffic to determine an appropriate maneuver	"Traffic, Avoid"
	Warning Alert	Notify ATC or other traffic as soon as practicable after tack	"Traffic, Maneuver Now"

II. Experimental Set up

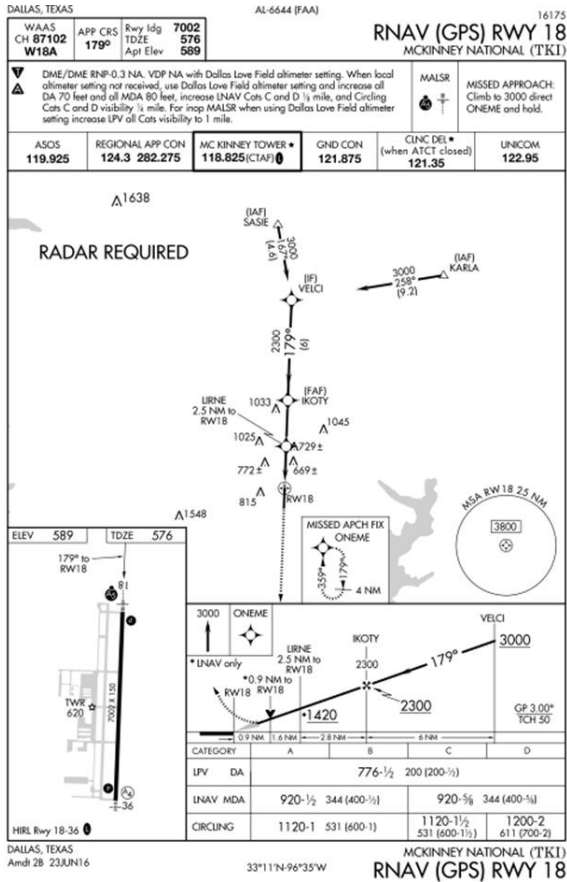


Fig. 3 Instrument approach to McKinney National Airport.

approach) or commanding heading, altitude, or speed changes. Turn rate and vertical rate were fixed parameters in the experiment. The subject pilot operated the Vigilant Spirit Control Station multiple times over the course of each hour. For each trial, the subject pilot selected a new aircraft, thereby transferring control away from the previous vehicle. The subject was capable of controlling the simulated UA aircraft via predefined waypoints or else manually with speed, heading, and altitude inputs. The tactical situation display featured an aviation map (Sectional Chart) with traffic and other information overlaid. A second display provided weather and instrument approach information. A radio communications panel was also available, although only one frequency was used for the TOPS2 experiment.

C. Multi-Aircraft Control Station

The multi-aircraft control system (MACS) is a NASA Ames designed research tool allowing a single user to control a large number of simulated

A. Ownship mission profile

The ownship vehicle was described to the subject pilot as a General Atomics MQ-9 Reaper Unmanned Aircraft to be flown at 90 KIAS along the RNAV GPS Runway 18 approach to McKinney National Airport (KTKI) in the Dallas Fort Worth area (Fig. 4). The start point was approximately 10-11 nmi from the runway threshold and on a 3-degree glide path. For purposes of the experiment, KTKI, which is normally Class D airspace, had issued a Notice to Airmen (NOTAM) that the control tower was out of service, which meant the subject would be operating in Class E airspace for the duration of each trial. By doing so, the experiment could later be run again using a controlled airspace (without a NOTAM) with minimal simulation development. Each run contained 7-8 six-minute *trials*, with two-minute interludes between each to fill out a post-trial questionnaire.

B. Vigilant Spirit Control Station

The Vigilant Spirit Control Station (VSCS) is a user-operated flight simulation station designed by the Air Force Research Laboratory. It is comprised of a tactical situation display and GUI elements that enable UAS control. The VSCS is capable of vehicle control handoff and traffic and comes equipped with a NAVAID database and map including approach charts for the experiment airports described in this document.

Within this experiment, the VSCS was operated by the subject pilot (Fig. 5). The pilot interacted with VSCS akin to operating an aircraft in autopilot commanding the UA to follow a predefined course (the instrument

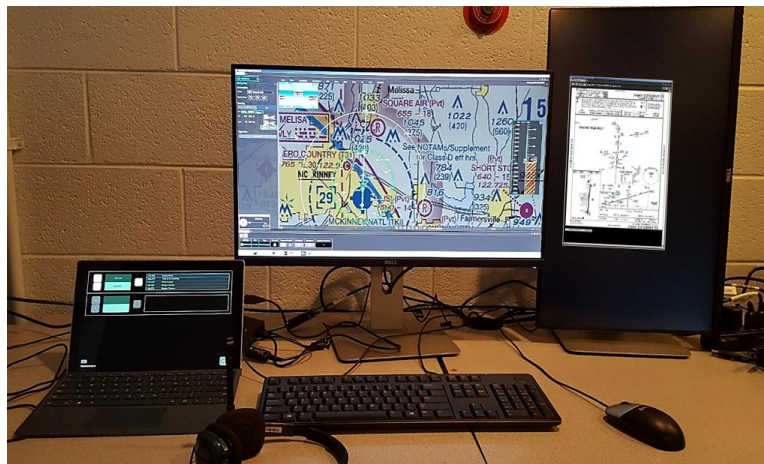


Fig. 4 Subject operated Vigilant Spirit Control Station.

aircraft through computer mouse input. MACS vehicles used in this experiment served as intruder and background traffic and were manned by TOPS2 team members who were licensed pilots and well versed in aviation radio communications. MACS operators monitored and communicated positions of the intruder and background vehicles on the local common traffic advisory frequency. As seen in Fig. 6, the station consisted of a dual-monitor display, mouse, standard QWERTY keyboard, and communications hardware. Each trial contained up to five simulated manned aircraft in or near the VFR traffic pattern: one intruder that would have a conflict with the UA and four that were background traffic. Which aircraft would be the intruder was known only to the research staff and communications for all MACS vehicles were parsed and varied between two operators from trial to trial. The background and intruder traffic consisted of the following vehicles: Cessna Citation I-SP, Cessna Conquest/II-441,



Fig. 5 Multi-Aircraft Control Station.

Cessna Skylane 182/RG, Embraer 135, Learjet 35/36, Mooney Mark 20, Pilatus PC-6A/B, Piper Aerostar 600/700, Piper Cherokee, Shorts 360, Sikorsky Skycrane, and TBM-700 Socata.

D. Subject Selection Criteria

Subject pilot recruitment sought an equal number of currently flying UAS and manned aircraft pilots for the experiment. Besides current flight experience, UAS pilots were required to have an instrument rating. Manned aircraft pilots were sought from commercial instrument flight instructors, corporate, and regional pilot pools in order to obtain a variety of experience and subjective feedback. Manned aircraft pilots were expected to have an instrument and commercial ratings, glass cockpit experience, and have flown within the past year.

E. Training

Selected subjects were given one hour of classroom training and approximately one hour of simulation flight training on the VSCS prior to conducting the experiment. Classroom training discussed the concept of operations, simulation components, and expectations of the subject pilot. Flight simulation training allowed the subject time to become used to the controls of VSCS, understand alerting conditions, and learn what maneuvering was viable when alerts occurred.

III. Experiment Variables and Testing Matrix

A. Independent Variables

In order to investigate the effects of variations in the DTA, two components of transitioning from En Route to Terminal DWC were investigated: (1) the geometry of the DTA (size and shape), and (2) whether the DWC definition switched between the En Route and Terminal definitions when the ownship crossed the DTA boundary or when the intruder crossed the DTA boundary.

1. DTA Geometry - Shape and Volume

While developing the experiment, researchers surmised that the size and shape of the DAA Terminal Area impact the level of safety and pilot acceptability. The DTA size is bounded between the two objectives: 1) minimize unnecessary alerting for aircraft operating closely around the VFR traffic pattern, and 2) maintain conservative En Route DWC alerting for all other aircraft. A smaller DTA is more likely to produce nuisance alerts for aircraft in the nominal VFR traffic pattern because of the larger En Route DWC alerting parameters. For example, an intruder aircraft entering the traffic pattern on a 45-degree entry may be projected to enter the ownship DAA Well Clear volume using En Route DWC parameters resulting in an alert prior to the intruder reaching the downwind leg of the VFR traffic pattern. Applying the Terminal DWC alerting parameters to this same geometry would result in no projected LoWC and, thus, no alert. Even if a LoWC was projected for the 45-degree entry, alerting would cease on the downwind leg because the track projection would be parallel to the ownship track and no longer projected inside the Terminal DWC volume. To avoid this undesirable En Route DWC alerting, the DTA should be sized such that the Terminal DWC is applied to these aircraft. A smaller DTA also runs the risk of degrading user trust in the system because those intermittent alerts do not precede an imminent LoWC nor require immediate action. In the case of a larger DTA, smaller alerting parameters are applied over a wider space, which could reduce the safety buffer for aircraft whose intent is not known (i.e., not following the standard traffic pattern). This may lead to alerts which occur too late for the operator to make a viable choice in the interest of safety and conflict avoidance.

It should be noted, DTA geometries were not depicted for the subject on the visual display, because subjective feedback and results were focused on pilot reaction due to alerting only.

Quadrilateral Prism DTA (Prism)

The quadrilateral prism DTA (or Prism DTA) encompasses a traffic pattern typical of light piston aircraft only. The rationale for the small prism DTA is that the wider traffic pattern flown by higher performance aircraft is too far away from the approach path to cause a Terminal DWC alert under normal conditions. Turbine-powered aircraft, when arriving or departing the airport via visual procedures, operate at higher speeds and require larger turn radii than slower piston-powered aircraft. Excluding the airspace where turbine aircraft operate near the runway, this DTA allows the larger En Route DWC to be applied to faster aircraft and affords the UAS operator additional protections and time to maneuver. The quadrilateral prism DTA is illustrated in Fig. 7. Latitude and longitude of runway ends provide the bounding of the Prism DTA, with a 0.5 nmi offset from the runway threshold and 1 nmi offset to the left and right of the runway centerline. The vertical limit was set at 2500 ft. AGL.

Cylinder DTA

The Cylinder DTA is a cylinder centered on an airport's reference point as published in the associated U.S. Chart Supplement. All public airports have a published reference point which is the approximate geometric center of all usable runway surfaces. The Cylinder DTA was sized at 4.4 NM radius and 2500 ft. AGL vertical limit, which is similarly sized to most Class D airspace (Fig. 8). One benefit to a cylindrical DTA would be a constant size and shape regardless of runway length and orientation. This also allows for non-standard traffic patterns caused by pilot variance while using geographic reference points to navigate the pattern. However, the larger volume would likely include some transit traffic. This presents a potential problem for the Cylinder DTA, as the intentions of those aircraft are unknown and potentially unpredictable while operating near the VFR traffic pattern. In such cases where an intruder's intentions are unknown, providing the UAS operator as much time to maneuver as possible is necessary and applying the smaller DAA Well Clear definition to these aircraft might not be sufficient.

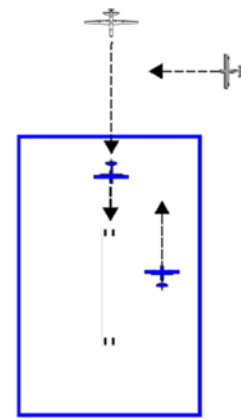


Fig. 6 Prism DTA (not to scale).

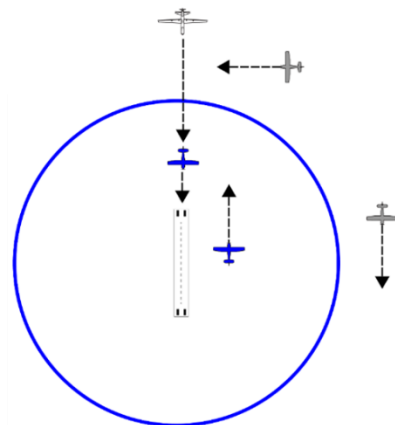


Fig. 7 Cylinder DTA (not to scale).

2. Switching: DTA Boundary Crossing by Ownship or Intruder

Given a specified DTA geometry, there are two considerations for switching from the En Route DWC to the Terminal DWC: ownship-centric or intruder-centric. For ownship-centric switching, the En route DWC definition is used until the ownship enters the DTA volume. Once the ownship crosses the boundary, the Terminal DWC is applied to all aircraft (Fig. 9) on the UA's traffic display. If the DTA is sized greater than the immediate terminal airspace, then aircraft beyond the traffic pattern with unknown intentions will have reduced DWC alerting criteria applied to them, which may cause late alerts to conflicts.

In the case of an intruder-centric switching, the En Route DWC definition will always apply to all aircraft outside the Terminal DWC boundary, and the Terminal DWC will always apply to all aircraft inside the DTA boundary (Fig. 9). This should allow for reduced separation in regions where vehicles are expected to move in predictable patterns and with less speed.

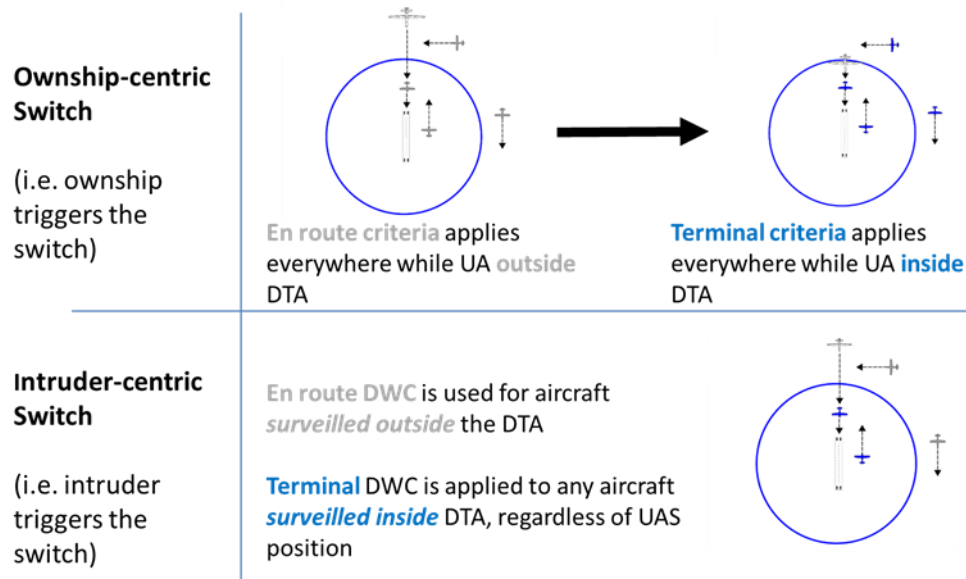


Fig. 8 Ownship- vs. Intruder-centric switching.

3. DTA Candidates

The combination of switching and geometry could produce four distinct DTA candidates: Intruder-centric Cylinder (IC), Ownship-centric Cylinder (OC), Intruder-centric Prism (IP), and Ownship-centric prism. Due to the 0.5 nmi runway threshold offset, the Terminal DTA definition would only be used when the ownship was about to land, and therefore would never be adequately tested. Since the ownship-centric prism DTA is so small, it was eliminated leaving only three remaining DTA candidates: IC, OC, and IP DTAs.

The Ownship-centric Cylinder DTA candidate was a 4.4 nmi radius cylinder centered on the airport reference point, which switched between En route and Terminal DWC parameters when the subject-controlled UA crossed the DTA boundary. The Intruder-centric Cylinder DTA candidate was sized the same but switched to Terminal DWC parameters when the *intruder* vehicle crossed the DTA boundary. Intruder-centric Prism DTA candidate was a quadrilateral box that bounded 1 nmi from the runway centerline and 0.5 nmi from the runway threshold; DWC parameters changed when the intruder vehicle crossed the boundary. All DTA candidates went from ground level to 2500 ft. AGL.

B. Nested Variables

1. Intruder Aircraft Type

As previously mentioned, both piston and turbine aircraft were represented within the variable set. Both had a low and high speed and were represented to the subject as either a Cessna 172, Cessna 210, Beechcraft King Air 200, or Gulfstream 500. Other background traffic existed within the simulation, but the scenarios were not designed for them to generate alerts. Please note, a subject maneuvering the UA in response to an intruder aircraft could cause an

unintended alert with background traffic. Any alerts resulting from background traffic were incurred by subject decision-making.

2. Intruder Vehicle Speeds

Average piston and turbine speeds are listed in Table 4. The Cessna 172 and 210 represented the piston low and high speeds, while the Beechcraft King Air 200 and Gulfstream 500 represented the turbine low and high speeds.

Table 4. Intruder aircraft speeds.

Intruder Aircraft	KIAS
Cessna 172	60
Cessna 210	110
Beechcraft King Air 200	110
Gulfstream 500	150

3. Conflict Geometries

Conflicts were defined based on three key intruder flight paths: Visual Flight Rules (VFR) Pattern, Base Entry, and Transit.

VFR Pattern

The VFR pattern intruders were modeled as flying a standard airport traffic pattern which consists of entering the airport environment at a 45-degree angle from the runway track, turning to the downwind leg parallel to the runway and opposite the landing direction, the base leg perpendicular to the runway, and the final approach which is aligned with the runway. For this encounter geometry, the intruder was modeled as both a piston and turbine aircraft. The key difference between these aircraft types are the typical speeds, and therefore, geometry relative to the airport. In general, piston aircraft are slower than turbine aircraft which is why piston aircraft are modeled as flying the downwind leg at a distance of 4000 feet from the runway centerline compared to the turbine aircraft distance of 8000 feet. Similarly, piston aircraft fly the downwind leg at a pattern altitude of 1000 feet while turbines fly at a pattern altitude of 1500 feet.

Base Entry

This encounter involves a simulated turbine aircraft that is inbound to land via an extended base leg in front of the UAS ownership before turning to the final approach leg. The path offset is 8000 ft. from the runway threshold and produces escalating preventive to warning level alerting, with recovery guidance depending on vehicle spacing. Piston base entry followed a 4000 ft. offset, and during simulation development proved to be a more benign example of the turbine path. This was because speeds for the piston aircraft were generally slower when compared to the turbine aircraft and allowed subject pilots more time to make a decision regarding a potential intruder. Therefore, turbine base entry was chosen as the more representative set and Base Entry Piston was not tested.

Transiting

This encounter involves a simulated single engine piston aircraft that crosses the approach path of the UAS ownership away from the immediate vicinity of the runway. The path offset is 18,000 ft. from the runway threshold and produces escalating preventive to warning level alerting, with recovery guidance depending on vehicle spacing. Piston intruders were specifically tested over turbines because they were most representative of vehicle cruise speeds encountered at the intersect altitude (2100 ft.). Since the slow-moving piston aircraft allowed the most time for the subject to observe alerting and respond, the piston intruder was surmised as the most benign example far away from the traffic pattern.

4. Conflict Severity

Since the alerting and guidance behavior during each trial is dependent on the active DTA configuration, each trial was designed based on the severity of the conflict. The trials were designed in two groups: pilot action expected trials, and no pilot action expected trials. In trials identified as ‘pilot action expected’, shown in red in Fig. 10, the separation between the UA and intruder aircraft is sufficiently small that a manned pilot would reasonably be expected to perform an avoidance maneuver to mitigate the conflict. In general, the pilot action expected trials invoke high-level DAA Warning alerts in both DWC definitions. Conversely, trials identified as ‘no pilot action expected’ are characterized by nominal separation seen in terminal environments and are shown in green in Fig. 10. These two groups are utilized in the results analysis section to broadly group the trials across a variety of conflict geometries.

For the turbine intruder on the VFR pattern, there were scenarios in which pilot action was expect and no pilot action was expected. In general, when a pilot action is expected on the VFR pattern intruders, the action is expected when the intruder turns from the downwind leg to the base leg, but in many cases, the DAA system would issue alerts while these intruders were on the 45 Entry leg of the pattern. If the subject pilot performed a DAA maneuver in response to the 45 Entry alert, the encounter was reclassified from ‘pilot action expected’ to ‘no pilot action expected’ as the pilot responded to an alert that did not preempt a loss of DWC. This is represented in Fig. 10 as the dashed green circle.

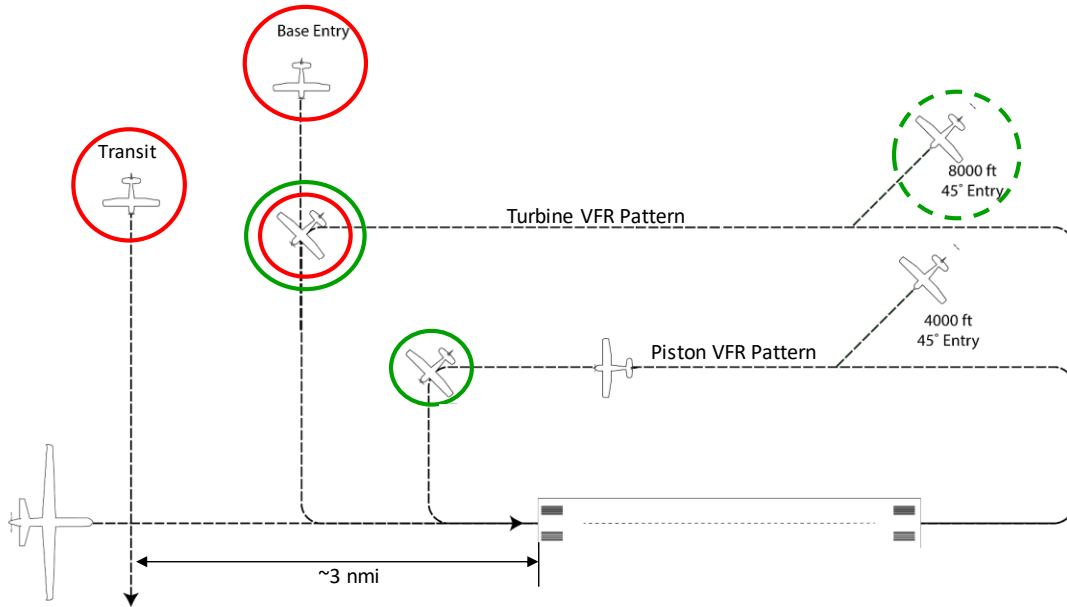


Fig. 9 Simulation vehicle paths.

C. Testing matrix

Nested variables were grouped into applicable sets for each DTA candidate in such a way that later analysis could make even comparisons between switching method (ownship/intruder) or geometry (cylinder/prism), simply because all three DTAs were dissimilar when applying both switching and geometry together. Each encounter set consisted of 7-8 trials and were bundled into hour-long *runs*, where each run represented a specific DTA/switching candidate. The runs were counterbalanced between subject pilots. Table 5 reflects the three different DTA types for three subjects, which provided a repeatable, counterbalanced matrix. The runs for each day were broken up into three testing periods. For every three subjects, each run type is repeated six times and appears twice in each testing period to nullify human factors effects in the analysis, such as morning drowsiness or afternoon exhaustion. The trials from the first day were repeated in a different order on the second day, but all aircraft tail numbers were changed to induce dissimilarity between trials.

Table 5. Subject run counter-balancing.

	Subject 1	Subject 2	Subject 3
Day 1	Cylinder Ownship	Prism Intruder	Cylinder Intruder
	Cylinder Intruder	Cylinder Ownship	Prism Intruder
	Prism Intruder	Cylinder Intruder	Cylinder Ownship
Day 2	Prism Intruder	Cylinder Intruder	Cylinder Ownship
	Cylinder Intruder	Cylinder Ownship	Prism Intruder
	Cylinder Ownship	Prism Intruder	Cylinder Intruder

IV. Data Collection

A. Objective Data

Objective data collected included simulated aircraft state data such as latitude, longitude, altitude, speed, and heading. Other data included slant range at closest point of approach to intruder aircraft, pilot input selections (button pushes) with timestamp, and alert type and duration with timestamp.

B. Subjective Data

Subjective data included background information questionnaires, post-trial questionnaires, post-experiment questionnaires, post-experiment debriefs with subjects and researcher observations. Questionnaires used a Likert rating scale to ask such questions as subject perceptions regarding the hazardousness of the encounter, perceived distance to the intruder, appropriateness of the time when alerts occurs, and general workload using the Bedford Workload Scale [11], due to the alerting.

V. Results

Metrics were compared across the three DTA candidates described in Section III. The key analysis was split into four categories of metrics: alerting performance, measured pilot response, separation, and subjective pilot data. Each of the metric categories are discussed herein.

A. Alerting Performance

The variations in alerting performance across the three DTA candidates is primarily driven by which DWC alerting scheme is applied to an intruder. Which DWC alerting scheme is applied is based on a combination of intruder and ownship positions relative to the runway. The alerting performance is characterized by the number of alerts issued, the duration of each alert, and the separation between the ownship and intruder aircraft when each alert is issued.

As mentioned previously, differences in the DTA candidates caused location-specific alerting dependent on the candidate. For example, the IP DTA resulted in Terminal DWC alerting for the piston aircraft only, because the turbine track remained outside the DTA boundary. In the case of the IC DTA candidate, only Terminal DWC alerting occurred for nearly all intruder types except high-speed transiting intruders for which En Route DWC alerts were briefly issued just prior to crossing into the DTA.

The overall number of alerts at each alert level across all subject pilots is shown in Fig. 11 separated by DTA geometry and conflict severity. For the Pilot Action Expected encounters in Fig. 11, the IC DTA issues lower-level En Route DWC alerts (i.e., Preventive and Corrective) and Terminal Warning alerts. The overall number of alerts is

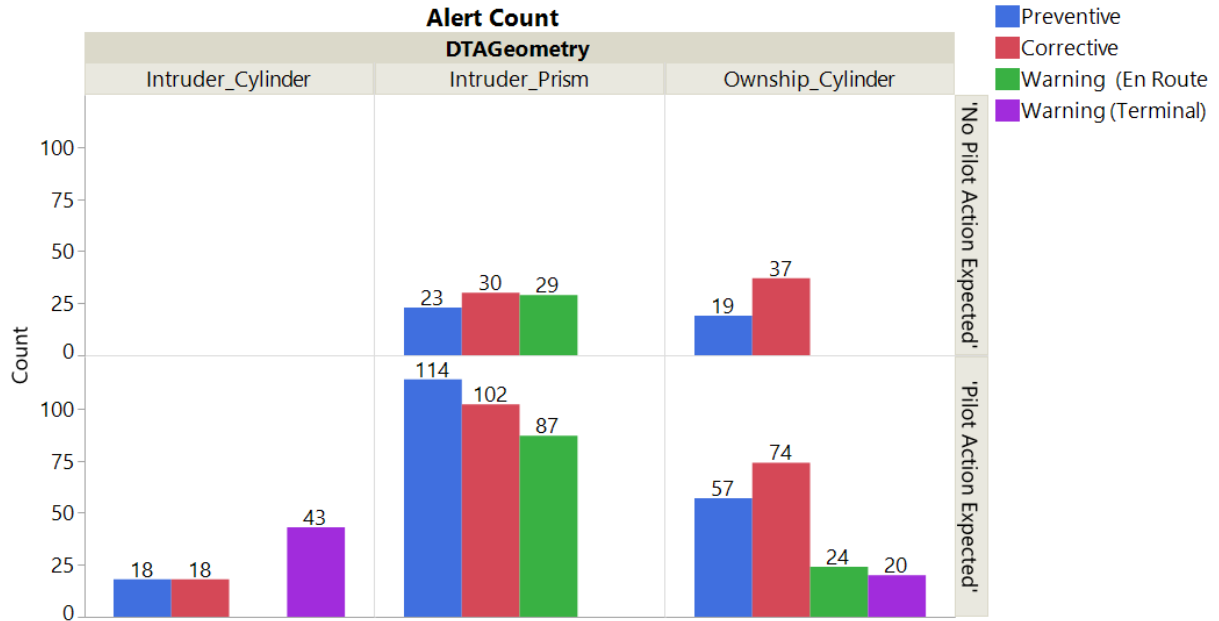


Fig. 10 Alert Count by DTA Geometry and Conflict Severity

much lower than the other DTA geometries, primarily due to the large reduction in En Route DWC alerts. The IP DTA issues only En Route DWC alerts with no Terminal DWC alerts. This DTA geometry resulted in the largest number of alerts issued. The OC DTA spans between the En Route DWC alerting and Terminal DWC alerting. That is, the OC DTA results in a high number of En Route DWC alerts up to warning-level while also issuing Terminal DWC alerts.

For the trials with nominally spaced intruder aircraft in which no pilot action is expected (top row of Fig. 11) the IC DTA successfully issues no alerts. The IP DTA issues En Route DWC alerts up to Warning-level, which is

undesirable for these intruders. The OC DTA issues several lower-level En Route DWC alerts but does not issue any Warning alerts which would require immediate pilot action.

For the trials with expected pilot action, there are warning-level alerts in all three DTA geometries. The IC DTA issued a few low-level En Route DWC alerts and Terminal DWC Warning alerts. Conversely, the IP DTA issued the most alerts and only issued alerts associated with the En Route DWC. Issuing both En Route and Terminal DWC Warning alerts, the OC DTA showed the greatest mixture of the two alerting schemes.

Overall, in terms of the number of alerts issued, the IC DTA performed best, then the OC DTA. The warning-level alerts issued on nominally spaced intruder aircraft is a very undesirable feature of the IP DTA.

Fig. 12 shows the distribution of cumulative duration of each alert type in a trial for all subject pilots. The figure is segmented by DTA geometry. If a single type of alert was issued more than once during the simulation run, the duration of all the issued alerts is summed in this figure. Below each distribution plot is the corresponding mean duration in seconds. In addition to each defined alert level, the figure also contains duration information on recovery guidance bands, which is a subset of the warning alert level. Per DO-365, a DAA system provides recovery guidance

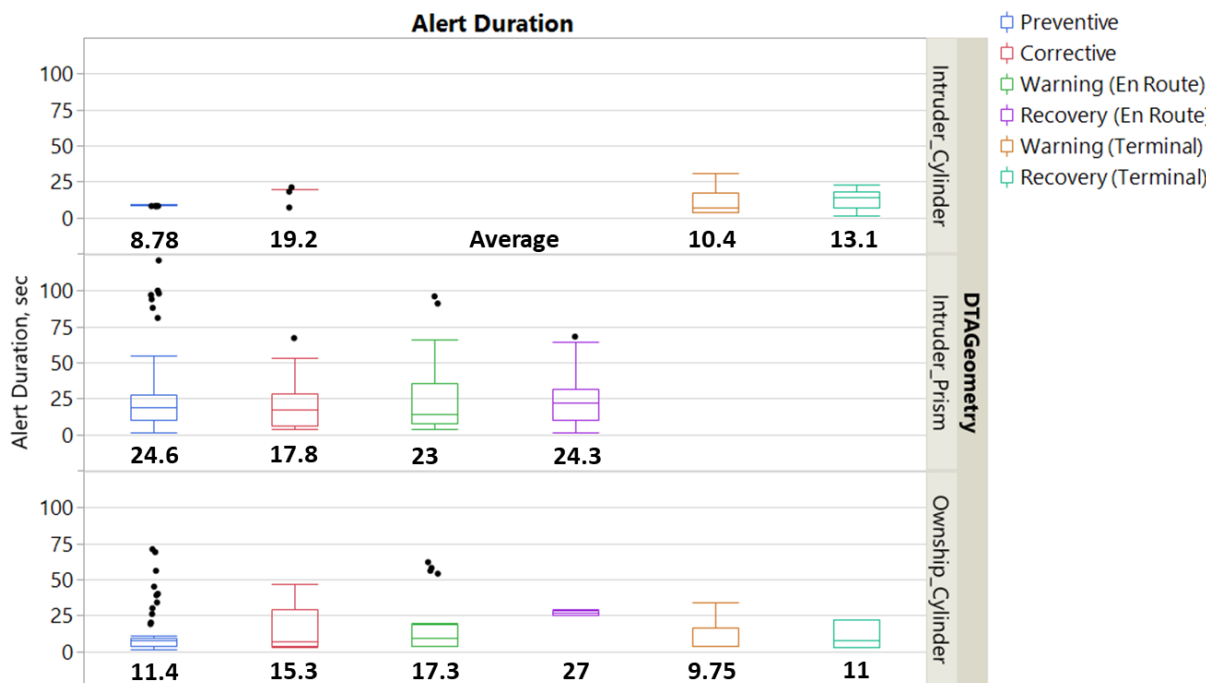


Fig. 11 Alert Duration by DTA Geometry

when a loss of DWC is unavoidable to reduce pilot response time. Subject pilots were trained to wait for an alert prior to maneuvering unless safety of flight was at risk. The En Route DWC Preventive and Corrective alerts enable pilot coordination with the intruder aircraft or ATC, if available, meaning those alerts are designed to be issued well before safety of flight is threatened.

The En Route DWC alerts issued for runs with the IC DTA applied lasted less than 20 seconds. Once the intruder entered the cylindrical DTA volume, the alerts ceased until the Terminal DWC alerting criteria was met. No subject pilot issued a maneuver to break off the approach in response to these lower-level alerts. With this DTA configuration, more than 75% of Terminal DWC Warning alerts lasted less than 25 seconds.

The IP DTA resulted in the longest alert duration with warning-level alerts remaining active for almost 100 seconds. Looking further into the data reveals that the 4 highest values for alert duration were associated with a single subject pilot that was comfortable getting closer to intruders than the DAA system was designed to protect.

The OC DTA configuration resulted in longer duration and more severe En Route DWC alerts. The Terminal DWC alerting behavior closely resembles the IC DTA configuration. However, IC DTA did not result in any En Route DWC Warning alerts or recovery guidance.

The final alerting metric, presented in Fig. 13, is the separation between ownship and intruder aircraft for every change in alert state. This metric is useful in understanding the encounter proximity when the subject pilots are alerted

to intruder aircraft. In Fig. 13, each alert level is represented by a unique color and the DWC definition is shown by the shape of the symbol.

The Terminal DWC alerting occurred for all DTA configurations with the aircraft less than 2 nmi apart. The En Route DWC alerted as far out as 6.5 nmi and had a substantial number of alerts farther out than 3 nmi.

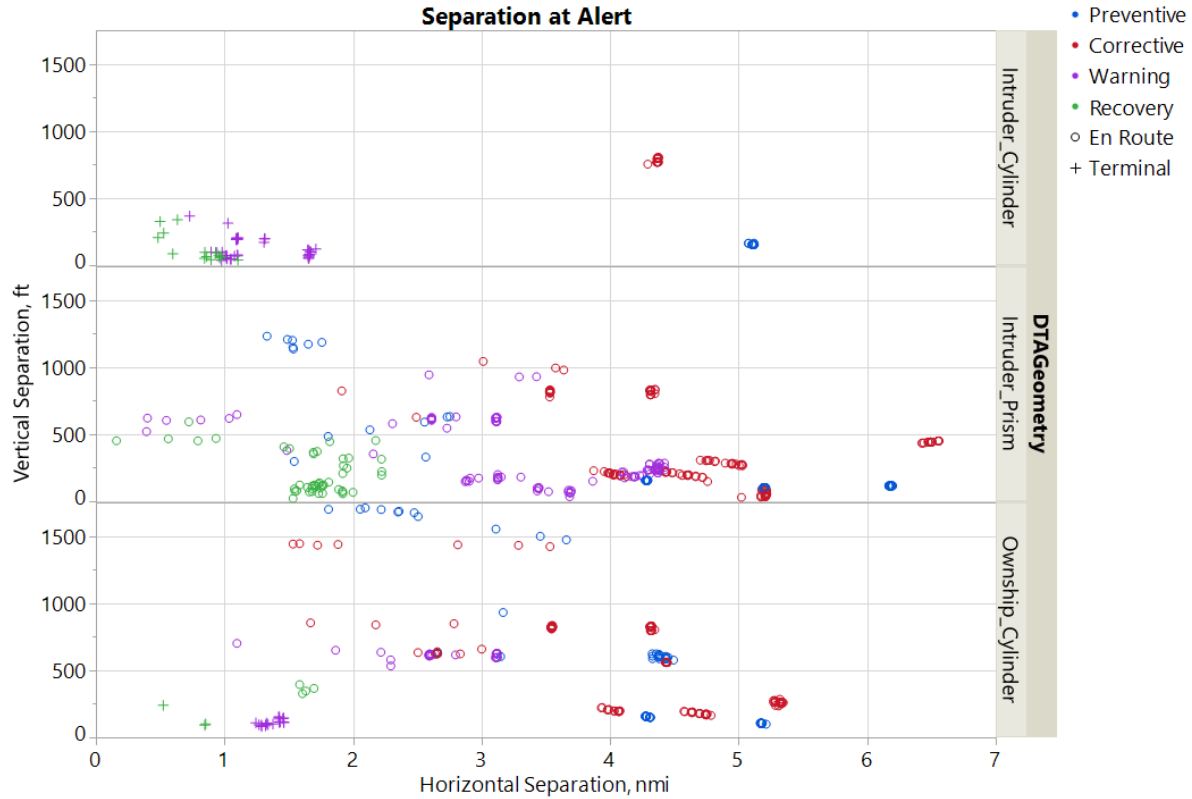


Fig. 12 Separation between ownship and intruder aircraft when alert is issued by DTA geometry.

B. Measured Pilot Response

Due to variations in the alerting and guidance, as well as subject pilots' experiences and preferences, key parameters with respect to the type of maneuver performed, the alerting and guidance that lead to that maneuver decision, and the time required for the pilot to execute the maneuver in response to an issued alert were evaluated.

Fig. 14 presents the first maneuver type selected and uploaded by the subject pilots segmented by DTA geometry and conflict severity. Three maneuver types result in the subject pilot commanding the UA away from the IAP: altitude, heading, or executing the missed approach. The Missed Approach Procedures (MAP) is the desired maneuver away from the IAP [7]. Researchers observed that commanded heading changes were generally associated with intruder aircraft turning in front of the UA in close proximity; the subject pilots chose to maneuver laterally away from the incoming intruder prior to executing the MAP or flying over the destination runway. Commanding speed changes was a common response to lower-level alerts, enabling the subject pilots to extend the timing of the encounter, providing more time for them to determine whether a MAP was appropriate. 'Maneuver Initiated' indicates that the pilot began to enter a command but never "sent" the command to the UA. This was often seen when an alert was issued on an intruder aircraft prior to the intruder maneuvering away from the UA's flight path, thus mitigating any need for a commanded maneuver from the subject pilots. Furthermore, this partial command was only seen in the encounters with no pilot action expected since these were the encounters that did not necessarily progress to a LoWC.

For encounters with no pilot action expected, the maneuvers were less varied. The few commanded heading and commanded altitudes were associated with pilots early on in their time flying in the simulation before they became more comfortable with the expected encounters surrounding the simulated airport environment. The OC DTA resulted in the most airspeed adjustments, primarily in response to the lower level En Route DWC alerts and large separation at the time they occurred.

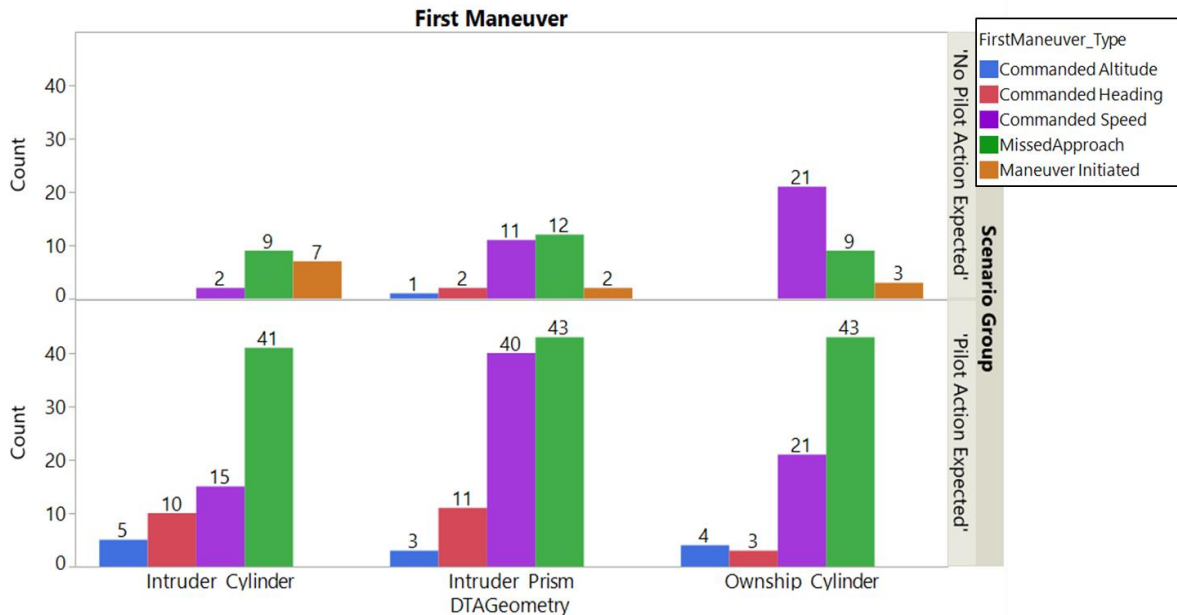


Fig. 13 First Maneuver Type by DTA Geometry and Conflict severity

The encounters in the 'Pilot Action Expected' group all require deviations from the IAP, which accounts for the high number of MAPs as the first maneuver. The next most common first maneuver was a speed adjustment, but in these encounter scenarios, this maneuver is insufficient and requires an additional maneuver to maintain DWC. The high number of heading change commands in the IC and IP DTAs are associated with intruder aircraft that are flying the downwind leg of the traffic pattern with no active alerts prior to turning to the base leg. On the other hand, the OC DTA issued alerts on these same intruder aircraft prior to the turn to the base leg resulting in the subject pilot's maneuvering prior to the intruder turning to the base leg which is a nominal condition in a terminal and should require no alert or maneuver.

The next metric presented in Fig. 15 shows the initial maneuver commanded by the subject pilot and the active alert to which the subject pilots respond. Fig. 15 is grouped by DTA geometry and from top-to-bottom increasing alert severity.

Fig. 15 shows that the majority of airspeed adjustments were made in response to lower level alerts up to En Route DWC Corrective; for higher level alerts, subject pilots preferred to execute the MAP. Subject pilots issued airspeed adjustments in the IP DTA more than others due to the increased number of En Route DWC Preventive and Corrective alerts associated with the IP DTA.

The display of recovery guidance promotes lateral maneuvers over vertical maneuvers due to the larger size of the compass rose and heading bands compared to the altitude tape and altitude bands. This trend is shown in the bottom row of Fig. 15; while there are still a majority of executed MAPs, the relative number of heading commands increases drastically.

There were a surprisingly high number of MAPs executed without guidance bands or alerting present. These cases primarily consist of two scenarios: 1) intruder aircraft beginning to turn from the downwind leg with no active alert to the base leg in front of the UA, or 2) intruder aircraft on the extended base leg or transiting the encompassing Class D airspace on which alerts have not yet been issued. For the former, the subject pilot's maneuver before an alert is issued for the intruder on the base leg. To provide an alert earlier, the DAA system would need to incorporate a more complex alerting systems beyond straight line projections, which is beyond the requirements specified by DO-365. With respect to the transiting or extended base entry intruder aircraft without alerts, the lack of alert or guidance banding when the avoidance maneuvers were issued indicates that the DAA system is not providing alerts aligned with the subject pilots' expectations. The early maneuvers only occurred with the Terminal DWC alerting for the extended base and transiting intruders.

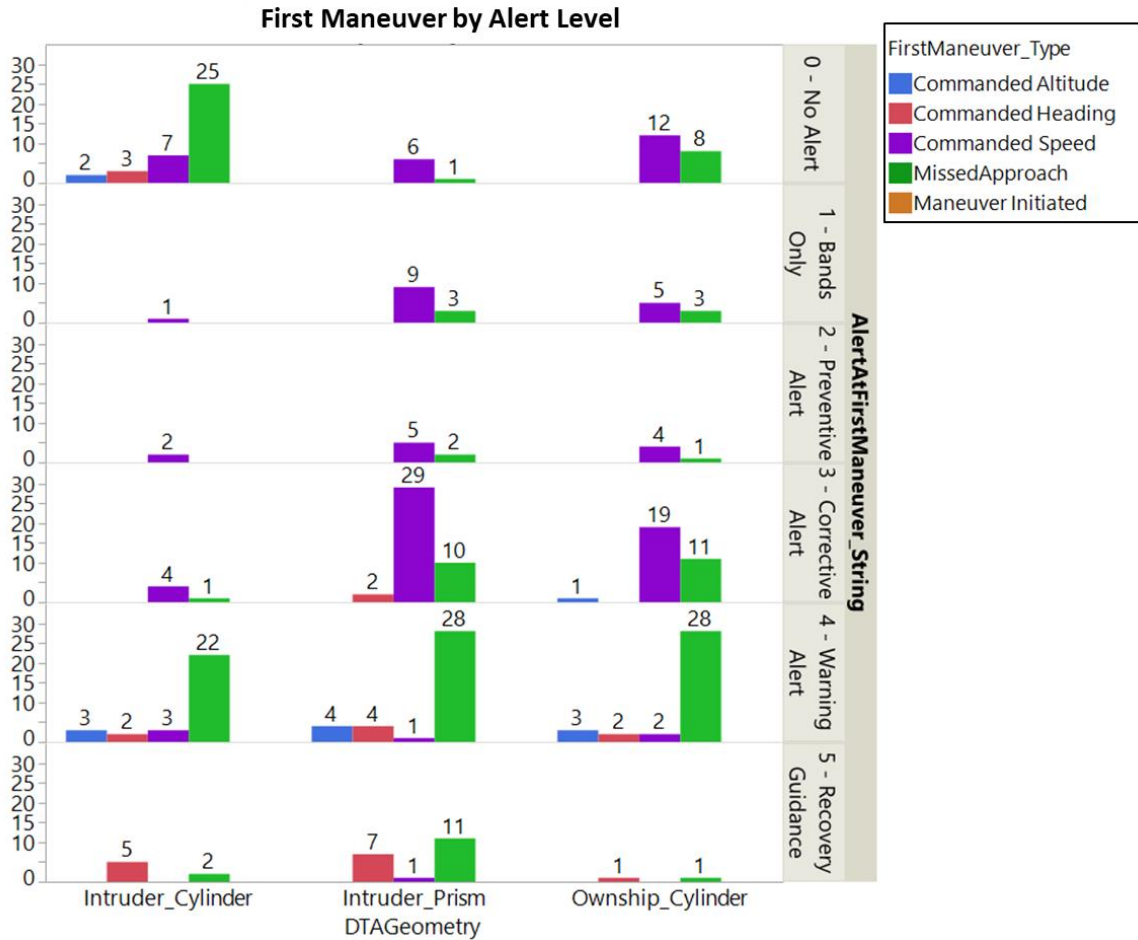


Fig. 15 Maneuver Type per Alert Level by DTA geometry

To better define the alerting parameters, researchers captured the relative time to loss of DWC when the subject pilots executed a maneuver to mitigate the encounter. Fig. 16 shows a cumulative distribution plot of this relative time to loss of Terminal DWC for the 14 simulation runs that met the criteria. To encompass the average time to LoWC, the alerting time must be raised above 43.8 sec.

In En Route operations, DAA guidance was designed to provide suggestive maneuver guidance in the horizontal and vertical dimensions independently. In the terminal environment, there is an operational restriction imposed on UA of approaching a destination runway via straight-in instrument approach procedures (IAP). The published IAPs and corresponding missed approach procedures, are designed with a

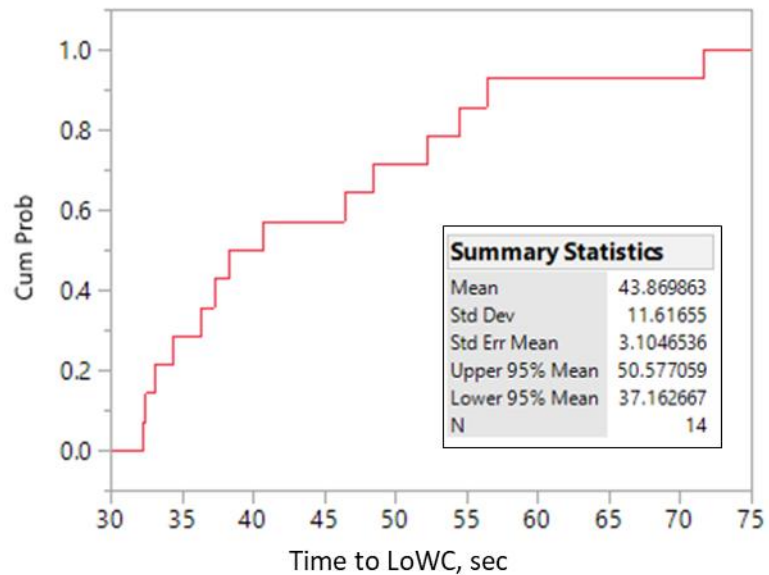


Fig. 14 Cumulative Distribution of Pilot Response prior to Loss of DWC

protected vertical corridor promoting vertical maneuvers if the IAP cannot be completed. Therefore, horizontal maneuvers are highly discouraged by UA once established on the IAP. Despite the preference for vertical maneuvers, the DAA guidance remained unchanged throughout this HITL experiment. That is, horizontal and vertical guidance was provided in association with both the Terminal and En Route DWC definitions.

Fig. 14 showed the first maneuver selected by the subject pilots including the large number of airspeed reductions which provided the subject pilots additional time to assess the scenario. To investigate the effect of the training to discourage horizontal maneuvers when the IAP cannot be maintained while still providing horizontal guidance, Fig. 17 shows the maneuver executed by the subject pilots resulting in deviation from the IAP. In Fig. 17, simulation runs in which the subject pilots only commanded airspeed changes or never finalized the command to the UA are grouped in orange.

In simulation runs with expected pilot action, both intruder-centric DTA cases resulted in the highest number of commanded heading changes, which is a maneuver not protected by the design of the IAP. The OC DTA configuration

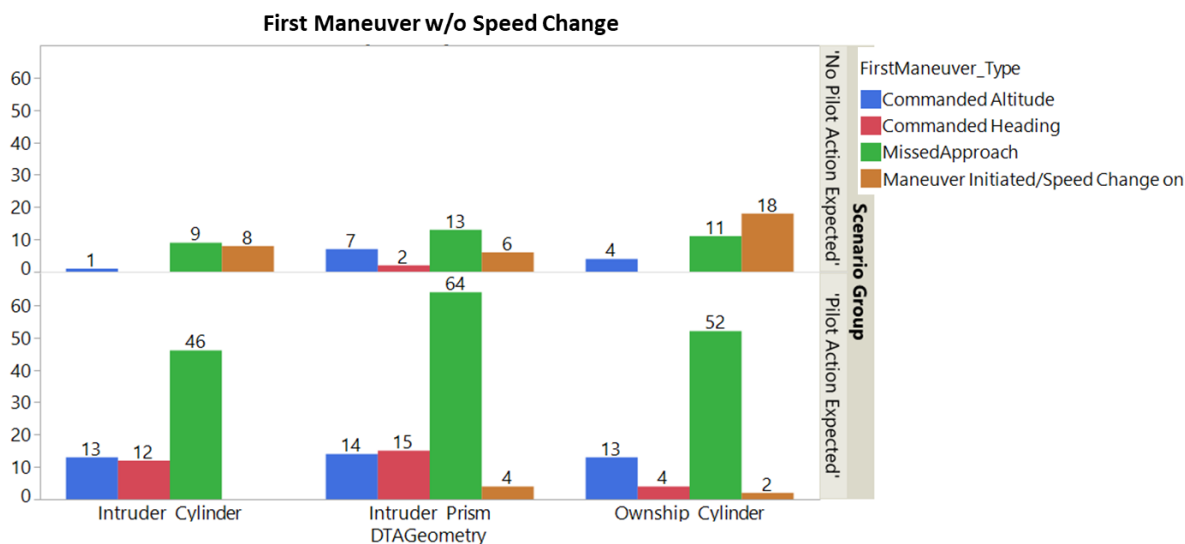


Fig. 16 First maneuver type without speed changes by DTA Geometry and Conflict Severity

saw the least number of these lateral deviations. It cannot be determined whether the pilots made these maneuvers because they knew there were no obstructions or without that consideration. In the cases with only speed changes or incomplete commands, the subject pilots felt comfortable despite failing to maintain DWC. Beyond these few cases, the majority of subject pilots executed the MAP in these scenarios.

The final metric of interest with respect to the subject pilots' maneuver selection was the amount of time, after the alert is issued, needed for the subject pilots to determine and execute the appropriate mitigating maneuver. Fig. 18 shows the pilot response time per alert level for each DTA geometry. The En Route DWC alerts had a consistent response time between the IP and OC DTAs. The response time to the En Route DWC Corrective alert in the IC DTA consists of the smallest number of data points primarily associated with speed adjustments. Subject pilots often preloaded the speed adjustment in anticipation of an alerting event. For Terminal DWC alerts, the response time was very quick. This may be due to the much closer proximity to the intruder when the alert was issued than the En Route DWC alerting criteria. The reduced proximity may make it easier for the subject pilot's to quickly determine the threat aircraft, that is, if they weren't already providing that nearby aircraft extra attention. To further exacerbate the trend, when subject pilots could anticipate the intruder aircraft prior to Terminal DWC alerts, they often preloaded a maneuver in preparation to respond to the alerts.

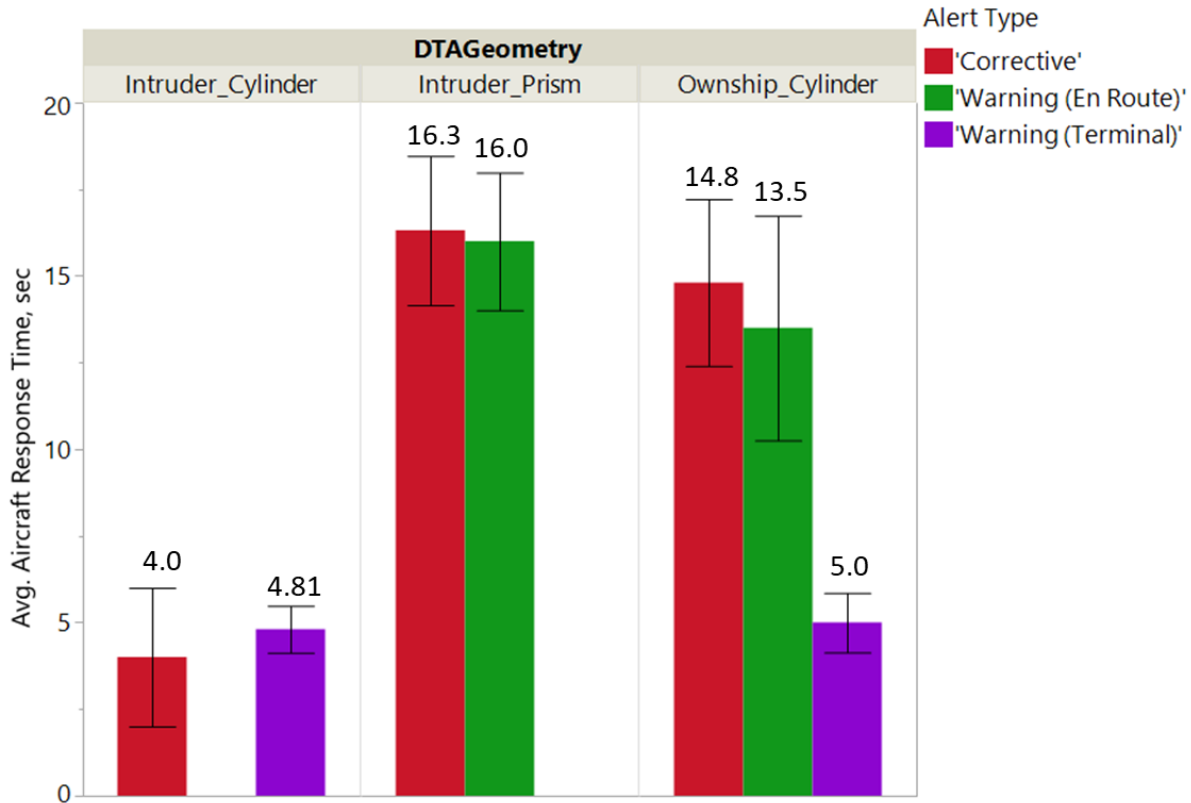


Fig. 17 Pilot Response Time per Alert by DTA Geometry

C. Achieved Separation

This section presents metrics focused on the impact of the measured pilot response from Section VI.B above. To determine if the selected maneuvers were sufficient in magnitude, orientation, and timeliness, researchers measured the minimum separation achieved during each simulation run as well as the severity of loss of DAA Well Clear.

Fig. 19 shows the very low rate of losses of Terminal DWC by DTA geometry. The situations resulting in LoWCs for all DTA geometries can be defined by 4 groups: insufficient alert time or delayed pilot response, late accelerating intruder, failure to follow DAA guidance, or user error. The 5 LoWCs due to late accelerating intruder are characterized by intruder aircraft turning from the downwind leg to the base leg of the traffic pattern resulting in a late alert. A single subject pilot caused 3 LoWCs by failing to follow the provided DAA guidance despite the numerous

Table 6. Reason for LoWC by DTA Geometry

Terminal LoWC Causes	Intruder Cylinder	Intruder Prism	Ownship Cylinder
Late Accelerating Intruder	4		1
Failure to Follow DAA Guidance	1	2	
User Error		1	
Insufficient Alert Time/ Delayed Pilot Response			1

aural alert annunciations and directive recovery guidance bands. There was a single LoWC induced by subject pilot input error delaying the maneuvering.

The final reason for LoWC was in a scenario with a non-accelerating intruder with full alerting time. Further examination showed that the subject pilot in this simulation run responded to the DAA alert slower than the assumed value. This LoWC could be avoided by either improving the subject pilot's response time or extending the Terminal DWC Warning alert time.

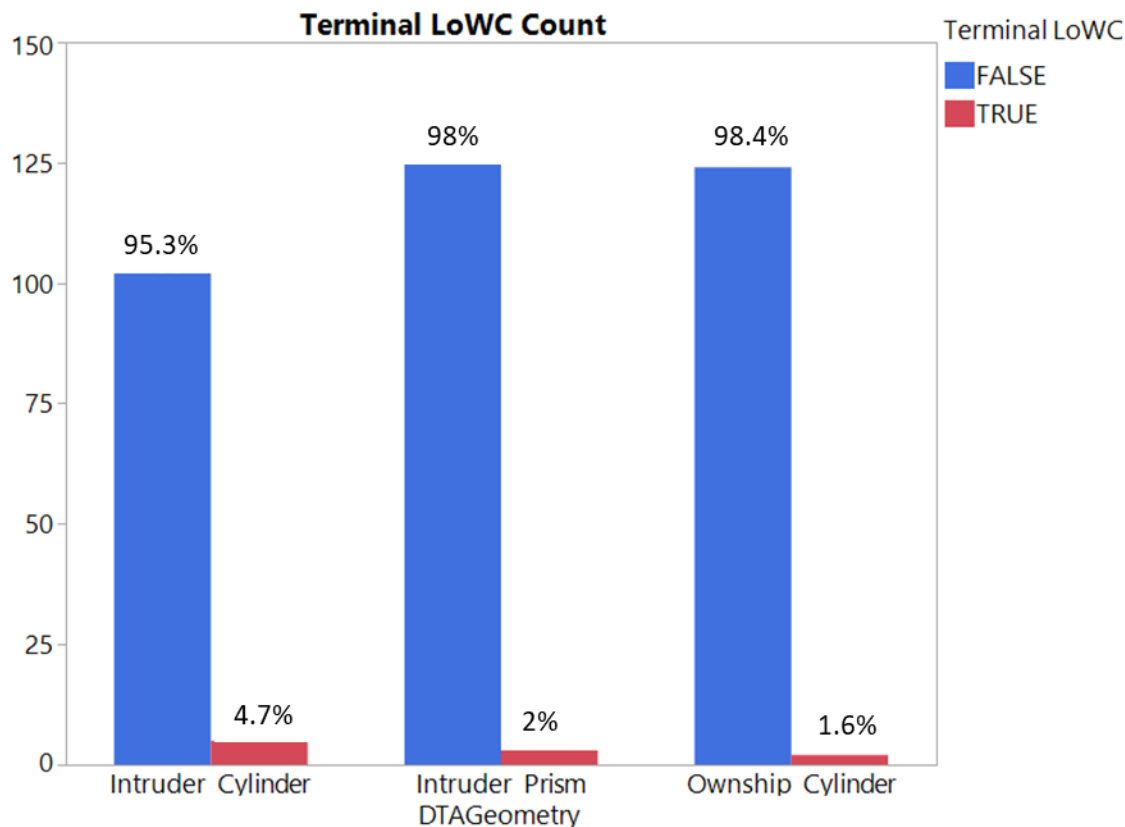


Fig. 18 Loss of DAA Well Clear Ratio by DTA Geometry

D. Subjective Data

A primary benefit of executing a HITL experiment is the collection of the subject's insights and perceptions that are not captured in fast-time computer simulation studies. For this experiment, the subjective metrics of interest primarily focused on the alerting behavior of the DAA system. In general, subjects were asked their perception of alert timing (earlier than desired vs. later than desired), distance between aircraft when an alert was issued (closer than desired vs. further apart than desired), and the pilot's perception of pressure to maneuver with respect to the guidance presentation throughout the trial.

Fig. 20 shows the distribution of three subjective metrics from surveying subject pilots at the end of each trial: timeliness of the alert, distance to intruder aircraft when the alert is issued, and pressure to maneuver based on the scenario. The timeliness of the alert ranges from 0% for 'much too late' to 100% for 'much too early'. Similarly, the distance to intruder when the alert is issued ranges from 0% for 'much too close' to 100% for 'much too distant'. The survey responses for these two metrics were very much aligned, as expected. Pressure to maneuver measures when the subject pilots felt the urge to maneuver with respect to the presentation of DAA guidance bands and ranges from 0% for 'felt pressure to maneuver prior to bands' to 100% for 'felt pressure to maneuver after the bands'.

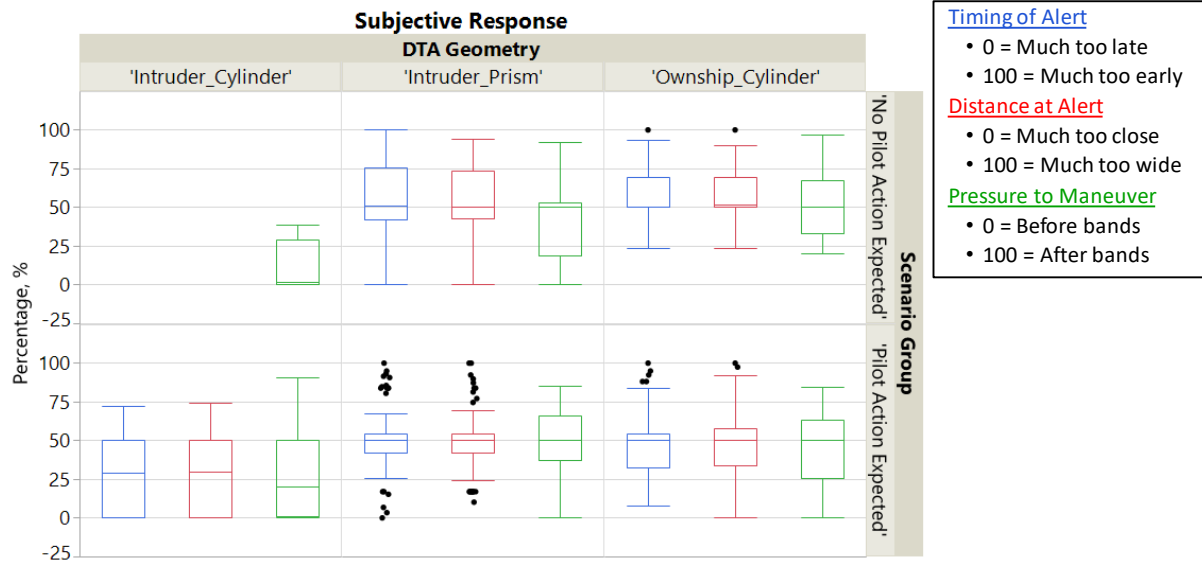


Fig. 19 Subjective Response Data by DTA Geometry and Conflict Severity

For the IP DTA, which maintained En Route DWC alerting throughout the trials in the study, the perceived timeliness and proximity to intruder for expected pilot action encounters is condensed around the 50% mark indicating the previously derived alerting scheme matches the subject pilot's expectations. Despite the favorable subjective response, this conservative alerting behavior restricts UA operations by forcing excessive MAPs.

Since the IC DTA provided mostly Terminal DWC alerting, the distribution of perceived timeliness and proximity shows the subject pilots felt the Terminal DWC alerts were issued later and closer than desired. Researchers hypothesize that increasing the alerting time as previously discussed may provide more desirable subjective responses.

VI. Summary

This section presents some key results of the HiTL study. The results presented herein focus on the alerting characteristic experienced by the subject pilots. The characteristics are presented separately for No Pilot Action Expected and Pilot Action Expected encounters.

Figure 21 and Fig. 22 show the alerting behavior of all three DTA candidates for the ‘no pilot action’ expected scenarios (green circles from Fig. 10) and the pilot action expected scenarios (red circles from Fig. 10), respectively. The box next to each leg of the VFR traffic pattern indicates the alerting behavior for each DTA candidate for intruders on that leg. The color of the alerting behavior indicates the researcher’s opinion of whether that alerting behavior is a positive feature (green) or a negative feature (red). In some cases, the behavior was not clearly positive or negative, those are shown in black.

A. No Pilot Action Expected

Figure 21 shows the alerting behavior of all three DTA candidates for the ‘no pilot action’ expected scenarios (green circles from Fig. 10). Since these are encounters in which no pilot action is expected, the lack of alerting for most intruder positions is considered a positive feature.

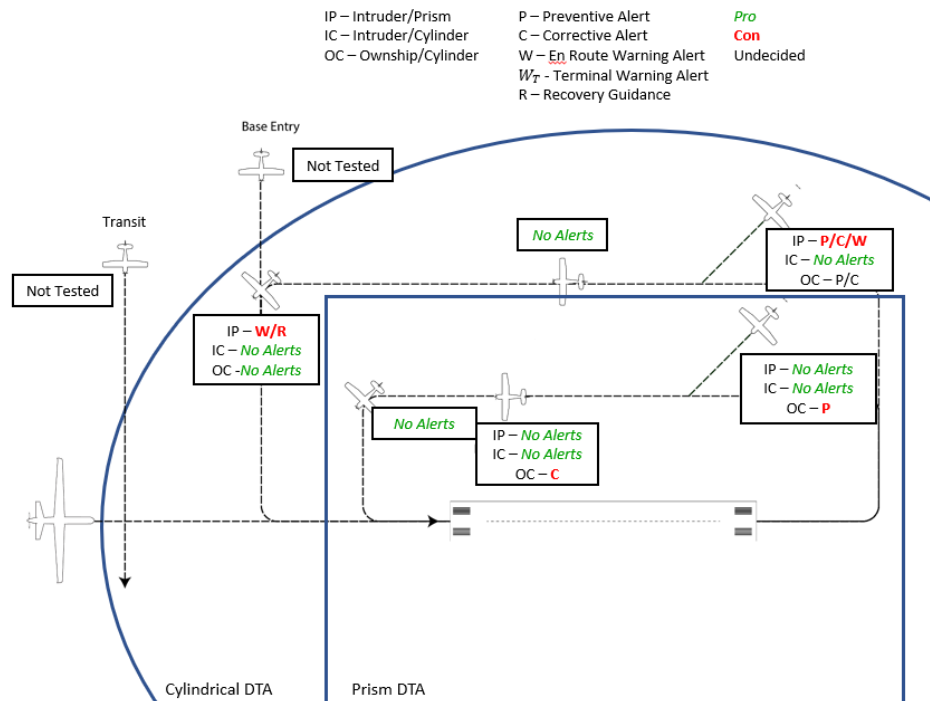


Fig. 20 Encounter-specific alerting performance – No Pilot Action Expected

The IP DTA receives the most alerts: up to a En Route DWC Warning alert for Turbine intruders on the 45-degree entry leg, and En Route DWC Warning alert and Recovery guidance for Turbine intruders turning from the downwind leg to the base leg.

The IC DTA receives no alerts for any of the scenarios in which no pilot action is expected.

The OC DTA has the most variation in the alerting. This DTA is the only one in which alerts may be issued on piston intruders flying the VFR pattern. This DTA also experienced some caution-level alerts (En Route DWC Corrective and Preventive alerts) for turbine intruders on the 45-degree entry leg of the VFR pattern. Several of the subject pilots showed a preference for this as an informational alert as opposed to a warning-level alert which is an immediately actionable alert forcing them to abandon the instrument approach. This alerting behavior is colored black in Fig. 21 as further discussion with requirement developers is warranted.

B. Pilot Action Expected

Figure 22 shows the alerting behavior of all three DTA candidates for the ‘pilot action expected’ scenarios (red circles from Fig. 10). In general, these encounters were designed to invoke alerts prior to a loss of DWC.

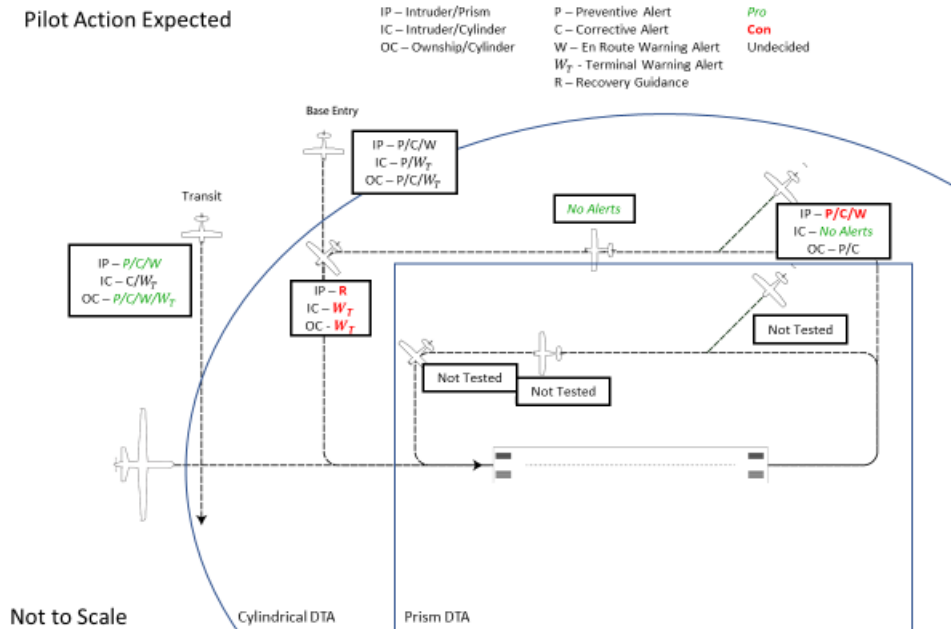


Fig. 21 Encounter-specific alerting performance – Pilot Action Expected.

Note that no cases were tested with pilot action expected for the piston intruder in the VFR pattern. Results for these aircraft would not change between the IC and IP DTAs. It was known from batch studies and previous HiTLs that these aircraft can cause alerts with the ownship as far as 8 nmi from the runway threshold while on an instrument approach, even for cases that no actual conflict is present. These alerts would happen with the OC DTA and they are not desirable. This was shown as red in Fig. 21 and that would carry to Fig. 22 if cases were run.

The IP DTA maintains the En Route DWC definition throughout the large majority of the encounters designed with pilot action expected. For turbine intruders in the VFR pattern, alerts as high as En Route DWC Warning alerts were issued on the 45 Entry leg of the traffic pattern. Pilots are trained to maneuver immediately at Warning Alerts; thus, mitigation maneuvers were often initiated while the intruder is on the 45-degree entry for many of these cases. Many pilots identified that the alerting on this intruder is not accurate as the intruder announced their intentions to join the downwind leg of the VFR pattern. Once on the downwind leg, no alerts were issued on the VFR pattern intruder until the turn to base leg in which all encounters went immediately to a loss of DWC and the associated recovery guidance. Recovery guidance without prior alert is an undesirable feature. For the base entry and transit intruders, the full span of En Route DWC alerting occurred up to a Warning alert if pilot action was delayed with the Corrective alert.

The IC DTA results in the earliest switch from En Route DWC to Terminal DWC; therefore, the majority of alerts issued are associated with the Terminal DWC. This results in no alerting for VFR pattern traffic until the turn from downwind to base leg at which point a Terminal DWC Warning alert is issued. For the base entry encounters, a few En Route DWC Preventive alerts were issued, but most of these encounters only issued Terminal DWC Warning alerts. For the transiting aircraft, En Route DWC Corrective alerts were issued prior to most Terminal DWC Warning alerts. The alerting on transiting intruders was deemed less desirable than the alerting associated with the other DTAs which remain in the En Route DWC longer.

Finally, the OC DTA has the greatest mix of En Route DWC and Terminal DWC alerting. For instance, for interactions with intruders in the VFR pattern, lower level En Route DWC Preventive and Corrective alerts were issued for intruders on the 45-entry phase while Terminal DWC Warning alerts were issued when the same intruder turned from downwind to the base leg. For the transiting and base entry scenarios, the full spectrum of En Route DWC alerts were issued as well as Terminal DWC alerts after the DTA switch occurred.

VII. Concluding Remarks

The NASA Langley Terminal Operations 2 experiment focused on three DTA candidates to better understand the effects of DTA size and traffic pattern paths, while ownship and intruder vehicles were used as triggers to test switching between the En Route and Terminal DWC definitions. A fractional factorial matrix was employed which targeted specific traffic pattern locations with potential conflict alerting inadequacies due to the Ownship Cylinder, Intruder Cylinder, and Intruder Prism DTA candidates. The results provided pros and cons of each of the three DTAs and there was no absolute answer. The Intruder Cylinder was considered to have the most important pros and least problematic cons. It was recommended to SC-228 for MOPS inclusion.

Subsequent subject matter expert discussions including the people involved in TOPS2 and others in SC-228 resulted in minor modifications being made to the recommended DTA. As of the publication date for this paper, the committee is considering an Intruder-centric Cylinder with a 4 to 5 nmi radius from the center of the runway and a height of 1800 to 2200 feet altitude above the runway. The size ranges are intended to support both sensor uncertainty and a buffer to keep the DTA from switching unnecessarily as a result of sensor uncertainty or intruder minor maneuvers. The TOPS2 team and SC-228 also developed an approach to make the DTA active or inactive to properly support phases of the UA flight and assure the DTA was only applied when the UA is taking off and landing.

Acknowledgments

The authors wish to express grateful appreciation to NASA researcher Michael Vincent for the initial experiment and hypotheses development, members of the NASA Langley Research Center Air Traffic Operations Laboratory for set up and conduct of the TOPS2 experiment, and also the SAIC software development team for their exceptional dedication to the development of a research simulation composed of regularly changing variables.

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