

SC-228 Inclusion of DAA Warning Alert for TCAS Interoperability

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Purpose and Background

This white paper summarizes NASA research results that have informed Special Committee 228 (SC-228) discussions and decisions regarding the inclusion of a warning-level alert within the detect and avoid (DAA) alerting structure for unmanned aircraft systems (UAS).

For UAS, the removal of the pilot from onboard the aircraft has eliminated the ability of the ground-based pilot in command (PIC) to use out-the-window visual information to make judgments about a potential threat of a loss of well clear with another aircraft. As a result, the DAA traffic display will be the primary source of information that the PIC can use to execute the three primary well clear functions: 1) detect a potential loss of well clear, 2) determine a resolution maneuver, and 3) upload that maneuver to the aircraft via the ground control station (GCS). In addition, pilots are required to coordinate with air traffic control (ATC) prior to maneuvering off of their approved flight plan. In determining an appropriate resolution maneuver to avoid a loss of well clear, the PIC must decide both when and how to maneuver, and both the timeliness and the accuracy (i.e., correctness) of the maneuver are critical to reducing the likelihood and/or severity of a loss of well clear.

Alerting information is one of three critical components of the DAA display, along with traffic information elements (e.g., relative heading, speed and altitude) and maneuver guidance. Alerting information and maneuver guidance, in particular, have been found to have a significant impact, both statistically and practically, on pilots' ability to avoid and minimize the severity of losses of well clear. While all three display components are key to pilots performing the traffic avoidance task of remaining well clear, in general, alerting information provides crucial information about *when* a resolution maneuver is required while maneuver guidance assists the pilot in determining *how* best to maneuver.

A fundamental task of the DAA alerting system is to provide critical timing information to the pilot about the potential for a loss of well clear with another aircraft. This is done by employing both temporal and spatial thresholds that indicate to the pilot the likelihood and imminence of a loss of well clear. The design of the DAA alerting thresholds is a balancing act between eliciting the desired pilot response in real loss of well clear threat events and reducing excessive, unnecessary, and/or uncoordinated UAS maneuvering within the air traffic environment; larger thresholds, both spatially and temporally, may increase the likelihood of a pilot avoiding a loss of well clear, but it can also increase the frequency of maneuvering — especially in cases where a maneuver is not actually needed to maintain well clear.

A series of human in the loop (HITL) simulations have been conducted as part of NASA's Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) project. The purpose of these HITLs has been to provide empirical results in order to inform development of the minimum human-machine interface requirements for the DAA system. This white paper will present those results which provide evidence of a human performance benefit (in terms of response times and ability to remain well

clear of other aircraft) of the DAA warning alert both with and without a collision avoidance system on board the aircraft.

Empirical Support for Inclusion of Warning Alert in DAA Structure






Alerting Structures

In order to show the relative performance benefits of the DAA warning alert, two alert structures will be compared: the “PT5 Alert Structure” and the “iHITL Alert Structure”.

PT5 Alert Structure

The warning alert level was included as part of the alerting structure in a HITL simulation experiment for the first time during NASA’s “Part Task (PT) 5” activity (Rorie, Fern & Shively, 2016). The alert levels and thresholds used in this simulation are shown in Table 1. This alert structure was based on the acceptance of a modified well clear definition recommended by the Sense and Avoid Science and Research Panel (SARP; Cook & Brooks, 2015; Walker, 2014).

Table 1. Alert structure and thresholds utilized in NASA’s PT5 simulation experiment.

| Alert Level | Separation Criteria | Time to Loss of Well Clear | Symbology | Aural Alert Verbiage |
|-----------------------------|---|----------------------------|---|-------------------------|
| DAA Warning Alert | modTau = 35 sec HMD = 0.75 nm DMOD = 0.75 nm ZTHR = 450 ft | 25 sec |  | “Traffic, Maneuver Now” |
| Corrective DAA Alert | modTau = 35 sec HMD = 0.75 nm DMOD = 0.75 nm ZTHR = 450 ft | 75 sec |  | “Traffic, Separate” |
| Preventive DAA Alert | modTau = 35 sec HMD = 1.0 nm DMOD = 0.75 nm ZTHR = 700 ft | N/A |  | “Traffic, Monitor” |
| DAA Proximate Alert | modTau = 35 sec HMD = 1.5 nm DMOD = 0.75 nm ZTHR = 1200 ft | N/A |  | N/A |
| None (Target) | Within surveillance field of regard | N/A |  | N/A |

Each alert level within the PT5 alerting structure was designed to indicate to the pilot the imminence of a potential loss of well clear (i.e., violation of the separation criteria), with another aircraft. The relative threat of a loss of well clear for each alert level is summarized below from lowest to highest threat level:






- *None*: no predicted loss of well clear
- *DAA Proximate Alert*: no predicted loss of well clear, however, a change in the horizontal or vertical trajectory of either aircraft could potentially result in a change in alert level

- *Preventive DAA Alert*: no predicted loss of well clear, however, a change in the horizontal or vertical trajectory of either aircraft could result in an immediate change in alert level
- *Corrective DAA Alert*: predicted loss of well clear within 75 seconds or less
- *DAA Warning Alert*: predicted loss of well clear within 25 seconds or less

iHITL Alert Structure

In the NASA DAA integrated HITL simulation (i.e., “iHITL”) prior to PT5 and the SC-228 acceptance of a well clear definition, the alert structure shown in Table 2 was used (Rorie & Fern, 2015). The alerting levels and thresholds in this alert structure was based on time to closest point of approach (CPA), and the collision avoidance alert level threshold was treated as equivalent to the well clear threshold (i.e., a collision avoidance alert would be triggered when well clear was lost).

Table 2. Alert structure and thresholds utilized in NASA’s iHITL simulation experiment.

| Alert Level | Separation Criteria | Time to Loss of Well Clear* | Symbology | Aural Alert Verbiage |
|---|-------------------------------------|-----------------------------|---|--------------------------------------|
| Collision Avoidance | HMD = 0.80 nm ZTHR = 400 ft | 0 sec |  | “Climb/Descend” “Turn Right/Left” |
| Predicted Collision Avoidance | HMD = 0.80 nm ZTHR = 400 ft | 70 sec |  | “Traffic, Traffic” |
| Self-Separation | HMD = 1.2 nm ZTHR = 900 ft | N/A |  | “Traffic, Traffic” |
| Preventive | HMD = 2.0 nm ZTHR = 900 ft | N/A |  | N/A |
| Proximal | Within surveillance field of regard | N/A |  | N/A |
| *Converted from time to collision avoidance alert, which occurred at 40sec to CPA, to allow for an easier comparison to the thresholds used in PT5. | | | | |

Each alert level within the iHITL alert structure was designed to indicate to the pilot the relative threat (i.e., loss of self-separation* or collision avoidance event) of nearby aircraft, summarized below from lowest-to-highest threat level.

- *Proximal*: not a current threat

* The term “self-separation” was used frequently early in the development of the SC-228 MOPS as an alternate description of the pilot task to remain well clear (i.e., maintain self-separation). Due to concerns from ATC organizations regarding the use of “separation” as a function that falls outside the scope of ATC responsibilities, the term was officially removed from the draft MOPS after the internal review and comment in August 2015. The term has been replaced with “traffic avoidance”.

- *Preventive*: no predicted loss of well clear (i.e., collision avoidance event), however, a change in the horizontal or vertical trajectory of either aircraft could potentially result in a change in alert level
- *Self-Separation*: no predicted loss of well clear, however, a change in the horizontal or vertical trajectory of either aircraft could result in an immediate change in alert level
- *Predicted Collision Avoidance*: predicted loss of collision avoidance event - i.e., loss of well clear - in (approximately) 70 seconds or less
- *Collision Avoidance*: well clear has been lost, now considered a collision avoidance event

Alert Structure Comparison

In order to more directly compare the different alert levels used in each simulation, Table 3 presents the alert levels according to whether there is a predicted loss of well clear, and if so, the time to loss of well clear.

Table 3. Side-by-side comparison of the iHITL and PT5 alert structures.










| PT5 Alert Structure | | Predicted Loss of Well Clear | Time to Predicted LoWC | iHITL Alert Structure | |
|---|----------------------|------------------------------|------------------------|-------------------------------------|---|
| Symbol | Level | | | Level | Symbol |
|  | None (Target) | No | N/A | Proximal |  |
| | DAA Proximate Alert | No | N/A | Preventive Alert |  |
|  | Preventive DAA Alert | No | N/A | Self-Separation Alert |  |
|  | Corrective DAA Alert | Yes | < 75 sec* | Predicted Collision Avoidance Alert |  |
|  | DAA Warning Alert | Yes | < 25 sec | N/A | N/A |
| N/A | N/A | Yes | 0 sec | Collision Avoidance Alert |  |
| *Corrective DAA alert becomes a DAA Warning alert at 25 sec to loss of well clear | | | | | |

Table 3 shows that the main difference between the two alert levels is the implementation of the two most severe alert levels in each structure. The highest two alert levels for each alert structure are depicted in Figure 1 along with their relationship to the well clear threshold. The difference between the highest, or warning, alert levels is examined first.

In the PT5 alerting structure, the warning alert level occurs 25 seconds prior to a predicted loss of well clear whereas in the iHITL alerting structure, the warning level occurs at the occurrence of a loss of well clear. Both implementations of the warning-level alert meet the guidance laid out by the Federal Aviation Administration (FAA) for the use of caution (yellow) and warning (red) symbology on flight

decks and specified in Advisory Circular 24.1322-1 [Department of Transportation (DOT), 2010]. According to this regulatory document, a caution alert is defined as “the level or category of alert for conditions that require immediate flightcrew awareness and a less urgent subsequent flightcrew response than a warning alert,” and a warning alert as “the level or category of alert for conditions that require immediate flightcrew awareness and immediate flightcrew response.”

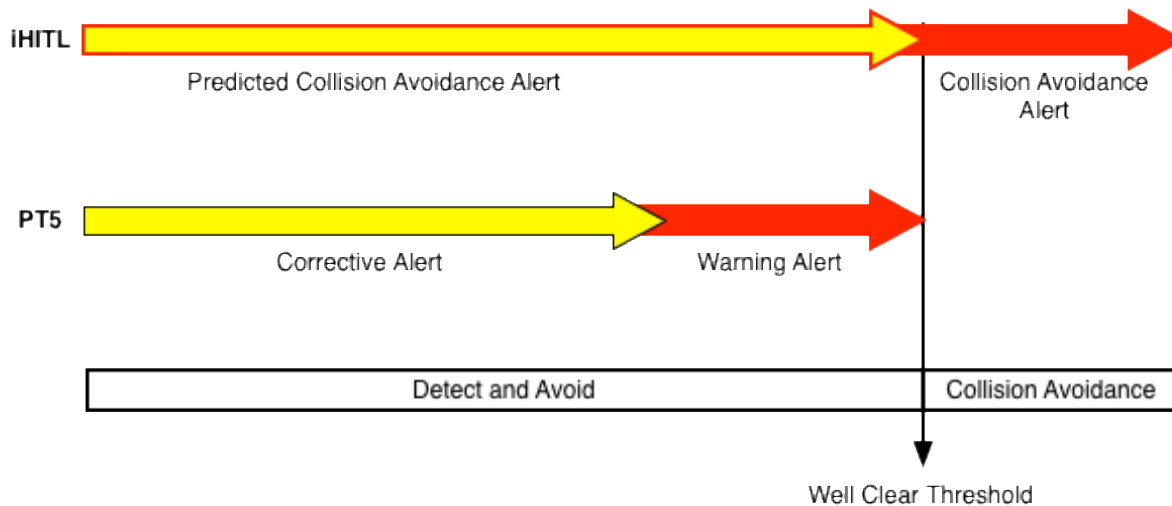


Figure 1. The relationship between the iHITL and PT5 caution and warning alert levels, and the well clear threshold.

In the PT5 alerting structure, the DAA warning alert indicates an imminent loss of well clear and the need for an immediate maneuver to avoid penetration of the well clear threshold. In the iHITL alerting structure, the warning alert indicates a loss of well clear and the need for an immediate maneuver to avoid a collision. While both of the alerts indicate a hazard situation and a need for an immediate maneuver, functionally they assist the pilot in accomplishing two different goals. The former provides a last indication to the pilot to avoid a loss of well clear, while the latter provides a last indication to the pilot to avoid a midair collision. Thus, as can be seen in Figure 1, the PT5 warning alert supports the DAA function of maintaining well clear while the iHITL warning supports a collision avoidance function, which is optional in the current phase of the DAA MOPS development.

The two implementations of the warning alert also impact the alert immediately preceding it. While the PT5 corrective alert and the iHITL predicted collision avoidance alert provide the same essential information to the pilot (that there is a predicted loss of well clear and a maneuver is needed), the temporal information (i.e., the relative imminence of a loss of well clear) provided to the pilot for each alert is different. For the PT5 corrective alert, the predicted time to a loss of well clear is roughly 25 – 75 seconds. At the 25 second threshold, the warning alert is triggered and alerts the pilot that there is less than 25 seconds to a loss of well clear. For the iHITL predicted collision avoidance alert, the predicted time to loss of well clear is anywhere from 0– 75 seconds.

As Figure 1 shows, the corrective and warning alerts in PT5 effectively replaced the predicted collision avoidance alert in iHITL (and the collision avoidance warning alert was removed). By doing this, the alert structure provided pilots with supplementary information regarding the time to a predicted loss of well clear. In comparison, the iHITL alerting structure contained more ambiguity regarding the amount of time pilots had to resolve an active threat. As will be shown in the next section, this difference in the

urgency and temporal information provided by the PT5 and iHITL alert structures has a significant impact on pilot response times and ability to maintain well clear.

Pilot Performance Comparison

Pilot Response Times

Response Time

Pilots' response times (i.e., measured response) can be deconstructed in a variety of ways, each assessing a different aspect of the pilot's response to a DAA alert. While higher-level metrics can give a sense of the pilot's overall response to a DAA alert, there are finer-grained metrics that address a specific component or stage of a pilot's reaction. The rest of this section will look at three different response time metrics in an attempt to clearly understand the impact of a DAA warning alert level on pilots performing the DAA task. The following results compare pilot responses to a predicted collision avoidance alert in iHITL, which indicated that the pilot had, at most, 75s before a loss of well clear, to pilot responses in PT5 to encounters that were a corrective DAA or DAA warning at first alert. Corrective at first alert indicated that pilots had at least 25s and, at most, 75s to a loss of well clear, while a warning at first alert indicated that pilots had no more than 25s to a loss of well clear. While the two simulations were evaluating substantially different displays, making direct comparison difficult, the trends between and within each experiment still provide insight into the performance effects of the iHITL and PT5 alert structures.

Aircraft response time, calculated as the time from the onset of the relevant DAA alert to the pilot's first upload to their aircraft, provides a broad look at pilot responses to a DAA alert. Namely, aircraft response time offers a global look at how quickly the pilot completed the major stages of the DAA task: detect a potential threat to well clear, determine an appropriate resolution maneuver, and execute that resolution maneuver. As shown in Figure 2, pilots in iHITL completed the task fairly quickly in response to a predicted collision avoidance alert, with aircraft response times ranging from 9.94s to 16.29s between display configurations. (Note: despite similar display labels between iHITL and PT5, e.g., "D1", the display configurations differed between experiments.) Figure 2 also shows that pilot response times in PT5 depended substantially on the threat type at first alert. Pilot response times were *at least* twice as long for pilots completing the task when responding to corrective alerts, which ranged from 18.25s to 27.01s, than when responding to warning alerts, which ranged from 7.71s to 10.43. While the aircraft response time data demonstrates that pilot responses to PT5 warning alerts were the quickest and most consistent overall, the metric is too coarse to offer insight into which aspect of the task – initiating a response or implementing a response – was responsible for these differences.

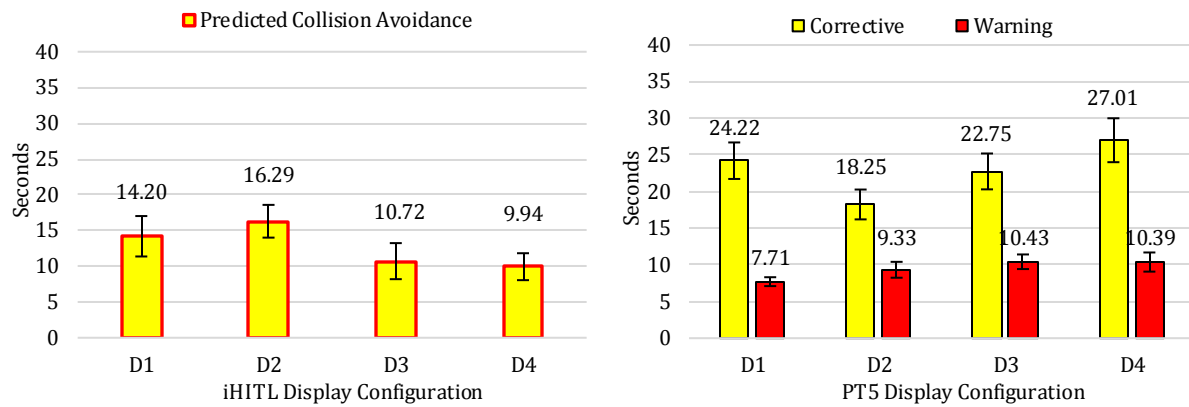


Figure 2. Mean aircraft response times for the predicted collision avoidance alert (iHITL, left) and the corrective and warning alerts (PT5, right).

Initial response time is a measure of the time between the onset of an alert and the pilot's first explicit attempt to make a change (i.e., edit) to their aircraft. The metric provides an indication of the urgency of the pilot's response and excludes any interaction time with the GCS command and control (C2) interfaces to actually input a response. As shown in Figure 3, pilots' initial response times in iHITL were consistent across display configurations, ranging 6.64s to 8.52s. The pattern holds for pilot responses to warning alerts in PT5, though quicker overall, where initial response times ranged from 3.83s to 4.78s. Initial response times to corrective alerts in PT5, however, were slower and much more variable than seen with the other alerts. Here, initial response times ranged from 9.57s to 20.67s. This metric therefore explains at least part of the reduction seen in aircraft response time for warning alerts in PT5 compared to both the iHITL predicted collision avoidance alert and the PT5 corrective alert: the presence of a dedicated warning alert minimizes the amount of time pilots spend waiting to initiate their response to a DAA alert.

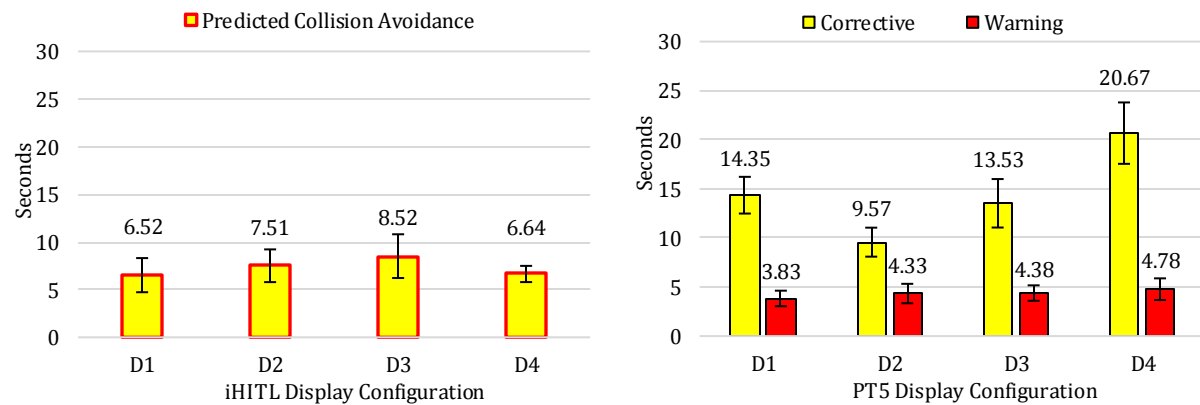


Figure 3. Mean initial response times for the predicted collision avoidance alert (iHITL, left) and the corrective and warning alerts (PT5, right).

The initial response time data also demonstrates that an alert level that unambiguously informs pilots that there is sufficient time for other tasks (i.e., the corrective alert in PT5), such as coordinating with ATC, leads not just to slower performance but also more variable responses across display configurations. Pilots in the "D4" condition in PT5, for example, spent a large amount of time utilizing a tool that allowed them to test the threat level of proposed heading or altitude maneuvers prior to

interacting with the C2 interfaces. While this increased their initial response time considerably in response to corrective alerts, pilots clearly understood that they did not have the same amount of time to utilize the tool in responding to warning alerts. The absence of an additional alert level for pilots in iHITL appears to have had a flattening effect on pilots' initial response times across display configurations. Comparing the initial response times in iHITL to those for corrective threats at first in alert in PT5, it appears that pilots in iHITL preferred to initiate maneuvers sooner rather than presume there was time for additional actions (such as coordination with ATC) regardless of display. However, their initial responses, on average, were not as urgent as those seen for the PT5 warning alert.

The other major component of the global aircraft response time metric is initial edit time, which refers only to the amount of time a pilot spent interacting with the GCS in order to implement an initial change (e.g., upload a newly commanded heading or altitude) to the aircraft. An unavoidable artifact of this metric is the influence of both C2 interface design and DAA display configuration, which directly affect how a pilot interfaces with both components of the GCS. However, no changes were made to the GCS C2 interface between iHITL and PT5, therefore most of the difference in edit time can be attributed to differences in DAA display configurations. As shown in Figure 4, display configuration had a pronounced effect on the variability of initial edit times in iHITL, which ranged from 2.20s to 8.79s. This result was not unexpected since the iHITL displays varied greatly in how assistive the conflict detection and resolution tools were (e.g., suggesting multiple resolution maneuver solutions vs. offering just a single one), as well as how tightly coupled they were to the C2 interfaces; both the D3 and D4 iHITL DAA display configurations had single resolution maneuver suggestions that were auto-loaded into the C2 interface. PT5, by contrast, intentionally minimized the variability in GCS integration between the DAA display by utilizing suggestive guidance designs (i.e., a range of maneuver solutions was provided) for all displays except the baseline (D1) condition and decoupling them from the C2 interface. As shown in Figure 4, initial edit times had a consistently smaller range in PT5 for both alert types. The range of initial edit times for encounters that began as a corrective alert was 6.34s to 9.87, while the range for warning alert encounters was even smaller, 4.17s to 6.05s.

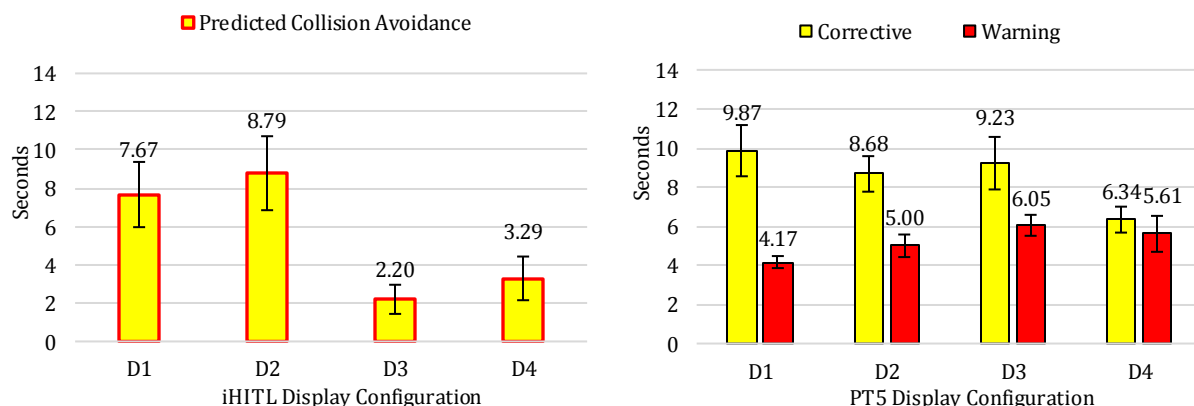


Figure 4. Mean initial edit times for the predicted collision avoidance alert (iHITL, left) and the corrective and warning alerts (PT5, right).

The initial edit time metric reveals once again how consistent pilot responses were to warning alerts in PT5 and suggests that pilots may have been nearing a floor in how quickly they could implement these changes given a specific instantiation of a GCS that did not have DAA guidance tightly coupled to the C2 interfaces. At the same time, the metric underscores the difficulty in comparing overall aircraft response

times between iHITL and PT5; while pilots were performing the same task in both studies, albeit with different alerting structures, they were equipped with very different DAA tools which had a large effect on how quickly they could implement ‘edits’. Taken as a whole, the response time data suggests that the DAA warning alert, compared to the iHITL predicted collision avoidance alert, spurred pilots to initiate their responses more immediately and complete the edit process as quickly as the control interfaces allowed, leading to a more efficient overall completion of the DAA task.

ATC Coordination

In order to ensure the interoperability of UAS with the air traffic environment, pilots of UAS will be expected to comply with the same operational rules as pilots of manned aircraft. A key area of concern with respect to pilots executing the DAA function is whether they will coordinate their traffic avoidance maneuvers off of their pre-filed flight plan prior to maneuvering to avoid a loss of well clear. The DAA MOPS currently specify that pilots utilizing the DAA system to maintain well clear will coordinate with ATC “as time allows”, and if coordination cannot be accomplished, the pilot “is authorized to deviate in order to remain well clear and avoid a collision with other aircraft”.

Figure 5 shows the proportion of maneuvers where pilots obtained an ATC clearance prior to maneuvering off of their flight plan by alert type. The results indicate that pilots treated the predicted collision avoidance alert and the warning alert similarly; the proportion of maneuvers executed to avoid a loss of well clear that received prior ATC approval was 34% and 23%, respectively. In contrast, pilots obtained ATC approval prior to maneuvering 65% of the time with the corrective alert.

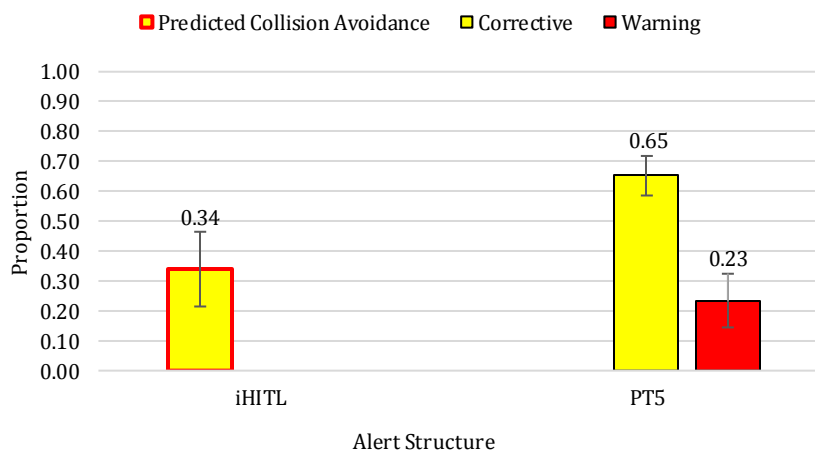


Figure 5. The proportion of encounters, by alert structure, where pilots obtained an ATC clearance prior to executing a maneuver to avoid a loss of well clear.

Again, the differences in the proportion of encounters that received prior ATC approval is likely due to the temporal information provided by each alert structure. With the PT5 alert structure, pilots knew that they had more time available when a corrective alert was present to coordinate a maneuver with ATC – if they ran out of time and needed to maneuver immediately, they would receive a warning alert. In contrast, the predicted collision avoidance alert within the iHITL alert structure gave no indication of how soon a loss of well clear would occur, and therefore, when a maneuver needed to be executed immediately (versus allowing more time to contact ATC). This appears to have led pilots to frequently prioritize maneuvering first over coordinating with ATC, rather than risk a loss of well clear. Despite this

apparent preference, however, pilots utilizing the iHITL alerting structure were not better at maintaining well clear compared to those utilizing the PT5 alerting structure.

Losses of Well Clear

The proportion of predicted losses of well clear that lead to an actual loss of well clear, for which the pilot was deemed at-fault, are shown in Figure 6. Overall, the observed proportion of losses of well clear in the iHITL simulation (0.03 – 0.14) are moderately higher than those observed in PT5 (0.00 – 0.09). Again, because the display configurations and test set ups cannot be directly compared, it is difficult to draw conclusions directly from just the proportion of losses of well clear observed in each experiment.

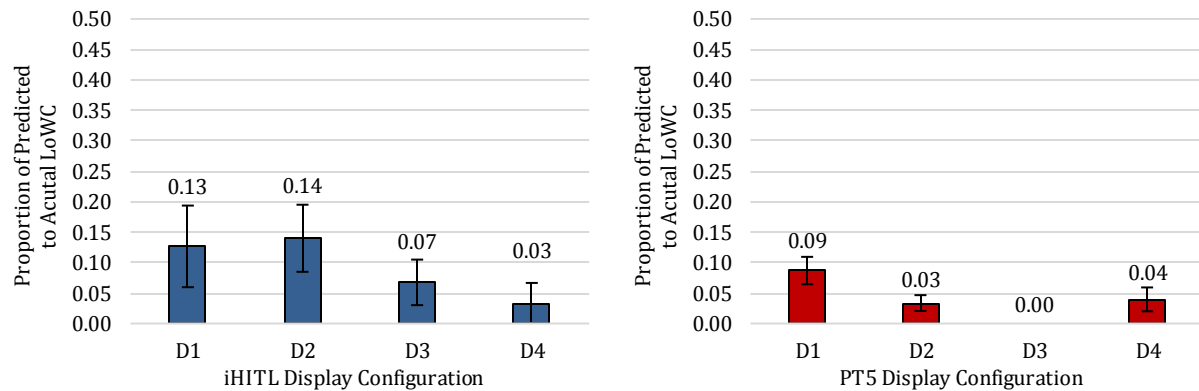


Figure 6. The proportion of encounters that were predicted to result in a loss of well clear that did actually did result in a loss of well clear, for the iHITL (left) and PT5 (right) alerting structures.

Table 4 provides additional evidence for the improved loss of well clear support provided by the PT5 alerting structure compared to the iHITL alerting structure.

Table 4 shows the proportion of losses of well clear by category of loss of well clear for which pilot responsibility was attributed. The losses of well clear for iHITL and PT5 were assigned one of three categories: ineffective maneuver, too slow, and too early return to course. An ‘ineffective maneuver’ occurred when the pilot did not make a sufficient maneuver to avoid the loss of well clear, even though they had enough time and the guidance was correct (in the conditions with available maneuver guidance). A loss of well clear was categorized as ‘too slow’ when the pilot was alerted to the threat with sufficient time to resolve it but did not respond quickly enough to avoid a loss of well clear. A ‘too early return’ loss of well clear occurred when the pilot successfully avoided a threat but returned to course before there was ample separation between the two aircraft and triggered a loss of well clear.

Table 4. The proportion of losses of well clear by category of loss of well clear for which pilot responsibility was attributed.

| | Ineffective Maneuver | Too Slow | Too Early Return |
|-------|----------------------|----------|------------------|
| iHITL | 0.21 | 0.79 | 0.00 |
| PT5 | 0.57 | 0.13 | 0.30 |

The above results show that in the iHITL, 75% of losses of clear were due to pilots executing maneuvers too slowly. This number dropped to 13% in PT5. Therefore, despite fairly short average aircraft response times for pilots in iHITL (Figure 2), there were nonetheless multiple instances where they were unsure of when an immediate maneuver was necessary and when they had time to engage in less time intensive actions (such as trial plan a variety of maneuvers or await for approval from ATC). In fact, as shown in Figure 7, pilots in the iHITL experiment were observed coordinating their maneuver with ATC even in instances where a loss of well clear was imminent. For alerts that appeared at 15 seconds or less to loss of well clear, when pilots should be immediately executing a maneuver, they in fact waited to receive approval from ATC 47% of the time. By comparison, pilots in PT5 were much less likely to attempt to coordinate their traffic avoidance maneuver at such a close proximity to a loss of well clear; at 15 or seconds or less to a loss of well clear, pilots waited to obtain prior ATC approval only 20% of the time.

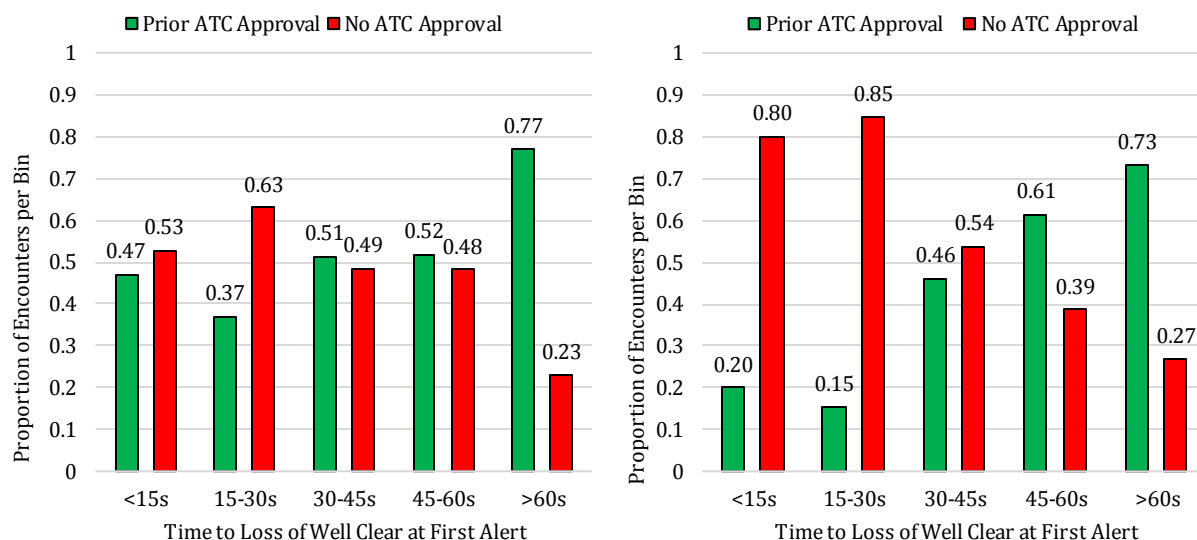


Figure 7. Proportion of pilot maneuvers per bin (e.g., <15s) in iHITL (left) and PT5 (right) with and without an obtained ATC clearance by time to loss of well clear at first alert.

Summary

The above results provide strong evidence for the performance benefits of including the DAA warning alert within the DAA alerting structure. The results presented above indicate that the DAA warning alert facilitates pilots' ability to respond quickly enough to avoid an imminent loss of well clear, while also supporting their determination of whether there is adequate time to coordinate their traffic avoidance maneuver off of their flight plan with ATC. These performance benefits result in both an increase in ATC interoperability — by increasing the frequency that pilots coordinate with ATC prior to maneuvering — as well as a reduction in the occurrences of losses of well clear, especially those that result from pilots executing resolution maneuvers too slowly as a result of attempting to obtain an ATC clearance.










Empirical Support for Use of the DAA Warning Alert with TCAS II Optional Integration

The following section presents empirical support for the inclusion of the DAA warning alert even when a UAS has been equipped with an optional TCAS II system. The addition of a TCAS II system to the DAA system will provide an additional layer of safety to prevent midair collisions. The existing TCAS II system has its own alerting structure that includes traffic advisories (TAs) and resolution advisories (RAs). With the integration of the DAA and TCAS II systems, the SC-228 DAA working group has reached consensus that the TCAS II TAs will be replaced by the DAA caution-level alerts [i.e., the corrective DAA alert and the preventive DAA alert (Table 1)]. When the DAA warning alert was initially proposed, it was assumed that it would be removed and replaced by the RA alert level if a manufacturer decided to implement a TCAS II system with the DAA system. However, observations from a preliminary data collection week from a NASA HITL indicated that the removal of the DAA warning alert, even when TCAS II was integrated, may result in undesirable pilot behaviors and system outcomes.

Alerting Structures for Cooperative Aircraft when TCAS II is Integrated

The NASA HITL (“mini-HITL”) initially included an experimental design that was intended to examine the performance of pilots on maintaining well clear and traffic avoidance when the DAA warning alert was maintained versus being removed from the integrated DAA-TCAS II alerting structure. This change in alert structure would only apply to cooperative intruders which could generate an RA; the DAA warning alert would be maintained for all other aircraft (e.g., non-cooperative) for which an RA would not be generated by the TCAS II system. Table 5 shows the two alerting structures for cooperative aircraft with and without the DAA warning alert.

Table 5. Comparison of the No Warning and With Warning alerting structures evaluated in NASA’s mini-HITL simulation.

| DAA-TCAS II Integrated Alerting Structures for Cooperative Aircraft | | | | | |
|---|----------------------|-------------------------|---|----------------------|----------------------|
| With Warning Alert | | | No Warning Alert | | |
| Symbol | Name | Aural Alert Verbiage | Symbol | Name | Aural Alert Verbiage |
|  | TCAS RA | “Climb/Descend” | | | |
|  | DAA Warning Alert | “Traffic, Maneuver Now” |  | TCAS RA | “Climb/Descend” |
|  | Corrective DAA Alert | “Traffic, Separate” |  | Corrective DAA Alert | “Traffic, Avoid” |
|  | Preventive DAA Alert | “Traffic, Monitor” |  | Preventive DAA Alert | “Traffic, Monitor” |
|  | None (Target) | N/A |  | None (Target) | N/A |

During the first week of two planned weeks of data collection, pilots were subjectively observed by researchers to be slower to respond when the DAA warning alert was not present, which resulted in a higher number of RAs. Although objective data could not be analyzed at the time, the decision was made to run the second week of data collection with the DAA warning alert for all intruders. The following section details the results of the data analyzed from the first week of data collection and the performance differences between the two integrated DAA-TCAS II alerting structures. Since the simulation system underwent some changes during the first week of data collection, it was not appropriate to conduct statistical analyses on this data. Nevertheless, the changes made were unlikely to have had a biased impact on pilot performance with one alert structure compared to the other; therefore, the descriptive statistics from this data still provide useful insight into the potential effect of removing the DAA warning alert in the integrated DAA-TCAS II alerting structure.

Pilot Performance Comparison

Response Times

As with the data presented for iHITL and PT5, pilot response times in the NASA mini-HITL were broken into multiple components. There were, however, several importance differences between the previous studies and the mini-HITL that are worth noting. The mini-HITL experimental set up utilized a pairwise encounter, or “part task”, design where pilots were exposed to a series of short (e.g., less than two minutes) as opposed to the “full mission” design of iHITL and PT5 where pilots completed 37-minute scenarios that included roughly eight encounters. This lower-fidelity set up resulted in pilots no longer having to contact ATC over a busy frequency (they merely had to ‘request’ a maneuver from the researcher, who was seated next to them at the GCS) or keep up with secondary tasks. These simulation changes, along with a much larger number of encounters per condition, likely led pilots to respond faster and more uniformly across this experiment than the previous simulations. Furthermore, the mini-HITL response time data in this paper only reports on pilots’ encounters against *cooperative aircraft* (i.e., those equipped with TCAS-II). Since the alerting structure for encounters with non-cooperative aircraft always contained a warning-level alert, they were left out of the present findings.

The mini-HITL experimental set up provided for an increased level of control over the encounter geometries presented to the pilot participants. This new ability allowed researchers to divide encounters into two distinct groups: those that provided pilots with the maximum look ahead time possible, given the alert structure (i.e., 55s to loss of well clear), and those that made a last-second acceleration (within roughly 10s of a loss of well clear) in the direction of ownship in order to force the triggering of a DAA warning or TCAS II RA. These latter use cases were referred to as “Blunders” and were intended to test aspects of the system that may not have been stressed had pilots been given sufficient time to resolve *all* of the scripted conflicts presented to them. The other use case, labeled “Non Blunders”, progressed to DAA warning or TCAS II RA alerts only if pilots neglected to take action after receiving ample time to respond. Consistent with expectations, 90% of the Non-Blunder encounters failed to progress to a DAA warning when the alert level was available. For this reason, the following response time data reports only on encounters against blundering aircraft.

Figure 8 shows pilots’ aircraft response times in mini-HITL as a function of the alert structure available to pilots (i.e., with a DAA warning or without a DAA warning alert). Pilots were found to respond slower overall when they did not have the warning alert (11.56s) compared to when the warning alert was available (7.02s). Figure 9 shows that the reductions in aircraft response times for the DAA warning condition were the result of reductions in both initial response times and initial edit times for pilots that had an alert structure with a DAA warning. Initial response times to

a blunder encounter were roughly 3s faster when there was a warning alert, while initial edit times were roughly 2s faster than when there wasn't a warning alert. Also of note in these results is the presence of less variability within the DAA warning condition. Pilots were far more uniform in each stage of their response to a blunder when a DAA warning was present compared to when it was absent (as evidenced by the shorter standard error bars).

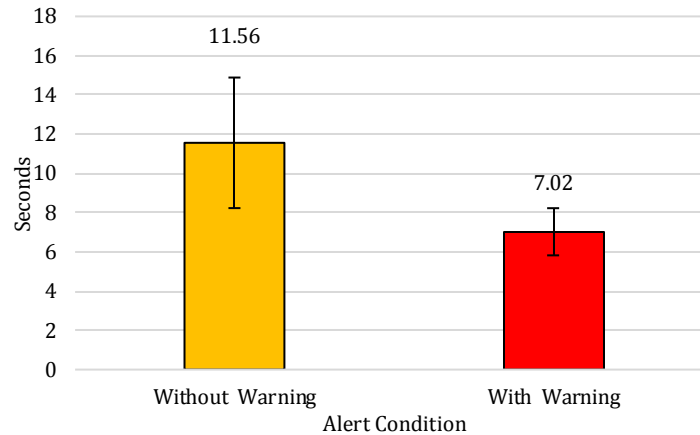


Figure 8. Mean aircraft response times against cooperative intruders that 'blundered' into ownship, by mini-HITL alert structure.

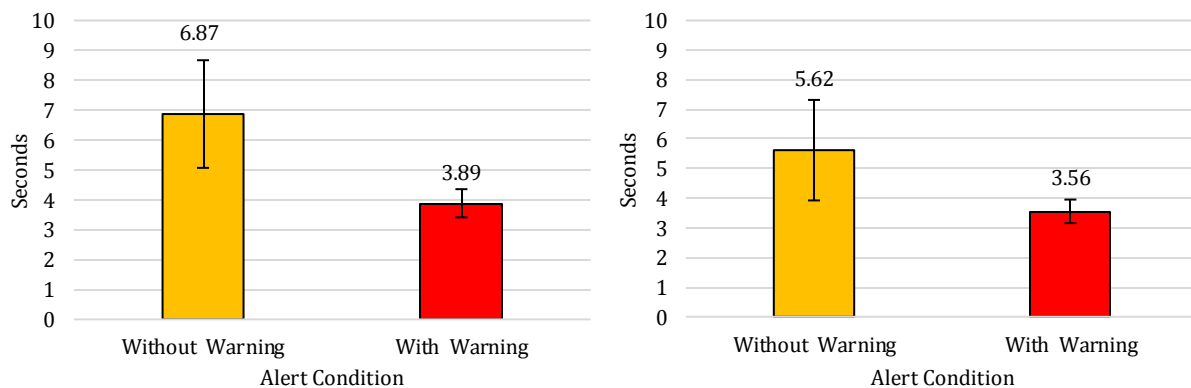


Figure 9. Mean initial response times (left) and initial edit times (right) against cooperative intruders that 'blundered' into ownship, by mini-HITL alert structure.

Proportion of Losses of Well Clear & Occurrence of RAs

The presence of a DAA warning alert was not found to have any impact on the proportion of predicted to actual losses of well clear or the frequency of TCAS II corrective RAs (i.e., those requiring a maneuver response by the pilot to avoid an imminent collision) in the NASA mini-HITL. This is likely more a function of the experimental design of the study rather than a reflection of the utility of inclusion of the DAA warning alert within the integrated DAA-TCAS II alerting structure. Since the experiment was divided into blunder and non-blunder encounters, pilots were either intentionally provided with insufficient time to resolve a conflict, as in the blunder encounters (where pilots had, at most 10s to a loss of well clear), or were given the maximum time possible under the alerting thresholds, as in the non-blunder cases (where pilots had the full 55s until a loss

of well clear). The loss of well clear and RA metrics bear this out: across all blunder encounters, pilots lost well clear 99% of the time and received a corrective RA 100% of the time (there were three instances of pilots receiving a corrective RA while they were well clear due to the specific encounter geometry). On the flip side, pilots never experienced a loss of well clear or corrective RA in any of the non-blunder encounters.

While the total absence of losses of well clear and RAs in cases where pilots had a maximum look ahead time for an encounter is indeed a positive finding, one should be cautioned against inferring too much from this result. As has been said, pilots had the benefit of a full alert progression. Just as critically, however, pilots were also less encumbered by secondary tasks throughout the mini-HITL experiment. There was no confederate ATC to communicate with over a busy frequency, nor a variety of other secondary tasks that had accompanied pilots in iHITL and PT5 (such as responding to chat messages and simulated system failures) that can take pilots' attention away from the task of remaining well clear. In general, this means that pilots responded more quickly and appropriately than would be expected in real world operations. In addition to this, the experimental design did not explicitly test the essential purpose of a DAA warning alert, which is to indicate to pilots that there was no longer any time to interact with ATC or extensively evaluate different evasive maneuvers. Had the experiment been designed with this in mind, there would have been more than just 2 encounter types (blunder/non-blunder); for instance, an encounter that alerted closer to the onset of a DAA warning – but not so close to an actual loss of well clear, such as 35s prior – could have tested the utility of a DAA warning in cases where the encounter was on the border of a corrective and warning alert. As it was designed, the mini-HITL experiment largely eliminated the ability of a DAA warning to impact the occurrence of a loss of well clear or RA.

While the proportion of losses of well clear or corrective RA metrics are not well suited to assessing pilot performance as a function of the DAA warning in the NASA mini-HITL, there are multiple well clear severity metrics that help shed light on the extent of the penetration of the well clear threshold in instances where well clear could not be maintained. Figure 10 shows the average duration of losses of well clear by mini-HITL alert structure. On average, losses of well clear that occurred without a DAA warning present lasted roughly 3 seconds longer compared to when the alert was not available.

In addition to slightly shorter loss of well clear durations, Figure 11 indicates that two measures of the severity of losses of well clear show better performance in the With DAA warning alert structure. The separation index, S_{index} , (Equation 1) is defined as the larger of the horizontal and vertical separations normalized by the required separation in each dimension where the $h_{sep_{CA}}$ and $v_{sep_{CA}}$ are the geometric portions of the well clear definition. When losses of well clear did occur, the separation index was slightly higher for the With Warning alert structure compared to the No Warning alert structure (58% vs 53% of the well clear spatial threshold was maintained), meaning that greater separation was preserved (or conversely, less penetration of the well clear threshold). The minimum separation severity metric is a measure of the minimum slant range distance between ownship and another aircraft. As seen in Figure 11, the With Warning alert structure had greater separation distances in cases where well clear was lost, on average, compared to the Without Warning alert structure (0.65 nm vs. 0.50 nm).

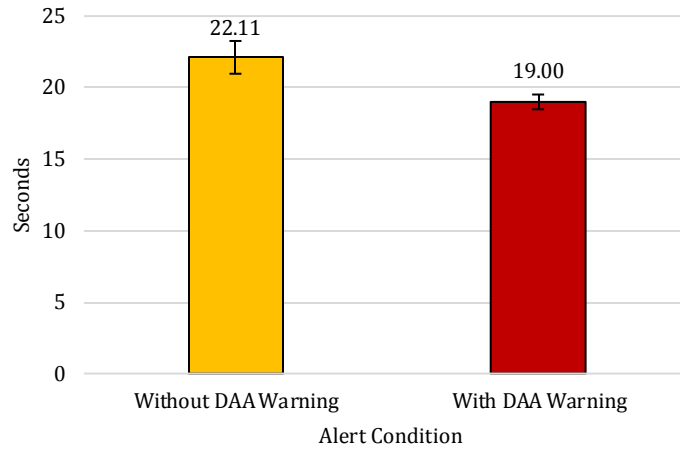


Figure 10. Mean duration of losses of well clear by mini-HITL alert structure.

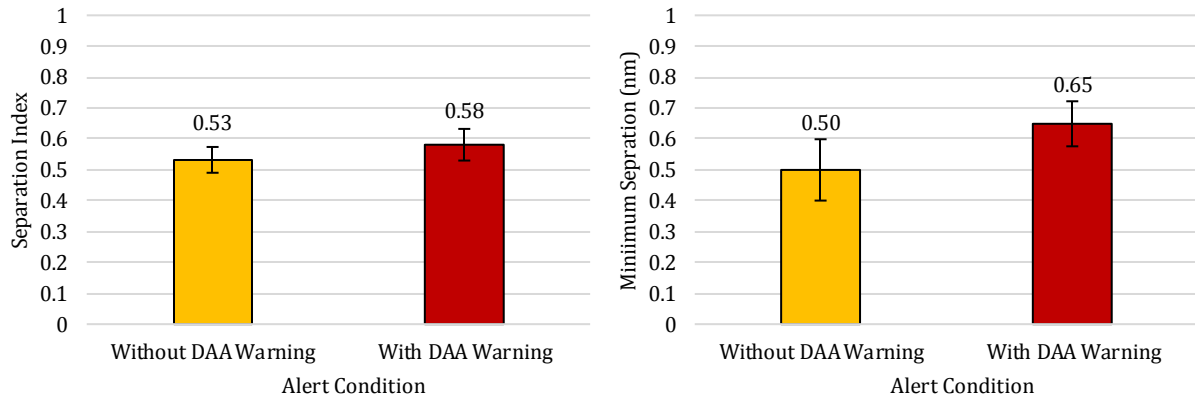


Figure 11. Two measures of the severity of losses of well clear for all encounters by mini-HITL alert structure: separation index (left) and minimum separation (right).

Equation 1. Separation Index

$$S_{index} = \min_t \left\{ \max \left[\frac{\text{horz. range}(t_i)}{h_{sep_{CA}}}, \frac{\text{vert. range}(t_i)}{v_{sep_{CA}}} \right] \right\}$$

Summary

The results from the first week of data collection of NASA's mini-HITL provides converging evidence for the inclusion of the DAA warning alert even when a UAS is optionally equipped with TCAS II in addition to the DAA system. When looking at pilots' response times to blundering encounters with the two different alerting structures, pilots were found to respond more quickly overall, and with greater consistency across pilots, when the DAA warning alert was present. While the occurrence of losses of well clear and RAs did not differ between alerting structures, pilots presented with the DAA warning alert were able to reduce the duration and severity of the violation compared to pilots without the alert. While the separation data reveals only moderate benefits for the DAA warning alert, it is likely that this is a greater reflection of the experimental design than it is of the two different alerting structures. Although the differences across all metrics were likely not

large enough to result in statistical significance, in the absence of any other data comparing the integrated DAA-TCAS II alerting structure with and without the DAA warning alert, it provides moderate empirical evidence that inclusion of this alert in the integrated alerting structure provides desirable performance benefits.

Conclusion

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