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Well Clear: General Aviation and Commercial Pilots' Perception of Unmanned Aerial Vehicles in the National Airspace System

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WELL CLEAR:
GENERAL AVIATION AND COMMERCIAL PILOTS' PERCEPTION OF UNMANNED AERIAL VEHICLES IN THE NATIONAL AIRSPACE SYSTEM

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ABSTRACT

WELL CLEAR:

GENERAL AVIATION AND COMMERCIAL PILOTS' PERCEPTION OF UNMANNED AERIAL VEHICLES IN THE NATIONAL AIRSPACE SYSTEM

The purpose of this research was to determine how different pilot types perceived the subjective concept of the Well Clear Boundary (WCB) and to observe if that boundary changed when dealing with manned versus unmanned aircraft systems (UAS) as well as the effects of other variables. Pilots' perceptions of the WCB were collected objectively through simulator recordings and subjectively through questionnaires. Together, these metrics provided quantitative and qualitative data about pilot WCB perception. The objective results of this study showed significant differences in WCB perception between two different pilot types, as well as WCB significant differences when comparing two different intruder types (manned versus unmanned aircraft). These differences were dependent on other manipulated variables, including intruder approach angle, ownship speed, and background traffic levels. Subjectively, there were evident differences in WCB perception across pilot types; general aviation (GA) pilots appeared to trust UAS aircraft slightly more than did the more experienced Airline Transport Pilots (ATPs). Overall, it is concluded that pilots' mental models of the WCB are more easily perceived as time-based boundaries in front of ownship, while being more easily perceived as distance-based boundaries to the rear of ownship.

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LIST OF ABBREVIATIONS

ANOVA = Analysis of Variance
ATC = Air Traffic Control
ATP = Airline Transport Pilot
CDTI = Cockpit Display of Traffic Information
CPA = Closest Point of Approach
CSD = Cockpit Situational Display
dOWN = Distance from Ownship
EMI = Electromagnetic Interference
FAA = Federal Aviation Administration
FARs = Federal Aviation Regulations
FDDRL = Flight Deck Display Research Lab
GA = General Aviation
GCS = Ground Control Station
IFR = Instrument Flight Rules
Kts = Knots
LOS = Loss of Signal
MACS = Multi-Aircraft Control Simulator
MIT = Massachusetts Institute of Technology
NAS = National Airspace System
NASA = National Aeronautics and Space Administration
NextGen = Next Generation Airspace System
NMAC = Near Mid-Air Collision
nmi = Nautical Miles
OTW = Out-the-Window
RTCA = Radio Technical Commission for Aeronautics
SAA = Sense and Avoid
SC 228 = RTCA Special Committee 228
SJSURF = San José State University Research Foundation
TCAS = Traffic Collision Avoidance System
tCPA = Time to Closest Point of Approach
UA = Unmanned Aircraft
UAS = Unmanned Aerial System
UAV = Unmanned Aerial Vehicle
US = United States
VFR = Visual Flight Rules
WCB = Well Clear Boundary

Introduction

Next Generation National Airspace System (NextGen NAS)

Our NAS is currently undergoing a major transition, as it is upgraded to the NextGen environment. Systems are moving away from traditional ground radar-based air traffic control to satellite-based systems and data connections for air traffic management. This vital upgrade is imperative to our NAS's future, which will face challenges of higher air traffic levels, more congested airports, and the need for precise timing and coordination to avoid a "gridlock" scenario in the skies (FAA, 2013). The NextGen NAS will allow a higher number of aircraft to fly closer together on more direct flight routes with the goal of reducing delays and providing unprecedented benefits for the environment and the economy through reducing carbon emissions and fuel consumption. It will ensure that our nation's skies have room for continued growth, increased safety, and reduced environmental impact (FAA, 2013).

Unmanned Aerial Systems (UAS)

Unmanned aerial systems (UAS) consist of an unmanned aircraft (UA) and all of the supporting equipment, control stations, data links, telemetry, communication links, and navigation equipment that work together to allow the UA to operate safely. The UA is piloted by humans working in a ground-control station, and other UAs can be controlled autonomously via on-board computers or communication links (FAA, 2013). UAS are entering a pivotal stage in their technological advancement with the corresponding need to become integrated into civilian operations. Many UAS aircraft originally designed for use in combat are now in high demand for use in the current NAS for a multitude of civilian and/or less traditional military roles. The potential that such UAS technology holds, if safely integrated into the NAS, is tremendous and its use can be highly beneficial to many sectors of society. For example, some of the currently proposed civil and commercial applications of UAS include: security awareness, disaster response, rescue team search and support, communications and broadcast, cargo transport, surface spectral and thermal analysis, vital infrastructure monitoring, commercial photography, aerial mapping and charting, and aerial advertising (FAA, 2014).

With their wide range of uses, the safe and proper integration of UAS into civilian airspace given current FARs remains largely a work in progress. Current ambitions and research initiatives issued to the FAA by the Congressional FAA Modernization and Reform Act of 2012 aim to have all regulations for UAS integration into the NAS in place by 2015. Section 322 of the House Bill, "…requires the Secretary of Transportation to develop a plan, in consultation with aviation and Unmanned Aircraft Systems (UAS) industry representatives, within nine months of enactment, for the safe integration of civil UASs into the National Airspace (NAS). This plan must contain a review of technologies and research to assist in this goal, recommendations for rulemaking on the definition of acceptable standards, ensure civil UASs have sense and avoid capability, develop standards and requirements for operators and pilots of UASs, and recommendations for all aspects of UAS integration. The plan must include a realistic time frame for UAS integration into the NAS, but no later than September 30, 2015" (U.S. House of Representatives, 2012).

UAS Technological Challenges

Although the FAA is pushing the future development of our NAS to include UASs, large challenges are still quite evident in our efforts to safely integrate UASs into our airspace. Perhaps due to the technological complexity of drones and their operators, very little media attention has examined the actual feasibility of pervasive domestic drone development. The important question to ask is whether it is even possible to have thousands of unmanned aircraft operating in our domestic airspace, which is already crowded with civilian and commercial air traffic. Exploring this feasibility further, it is important to note vulnerabilities UASs may have in their inherent architecture. In order to be controlled from a remote location, UASs must communicate with pilots on the ground through a data link. This link is, as are all wireless communications, vulnerable to electromagnetic interference (EMI). One of the major issues surrounding the viability of UAS integration is what happens when a link is lost between a UAS ground control station (GCS) and its unmanned aircraft? Sometimes the link can be reestablished quickly, but there remain many instances in which reconnection attempts have failed and have led to unintended consequences (Public Intelligence, 2012). This issue of lost-link events is considered "a major concern and failure of communications due to EMI has resulted in numerous UAS accidents" (p. 78) according to a 2010 U.S. Army Command and General Staff College Report (Major Yochim, 2010).

As recently as 2011, an unmanned drone collision with a manned aircraft occurred in Afghanistan between a RQ-7 Shadow UAV and an Air Force Special Operations Command C-130. Luckily, no one was hurt or injured, but the collision completely obliterated the UAV and caused major ruptures to the wing fuel tank and the wing box of the C-130 (Reed, 2011). Had it not been for the sheer difference in size between the small UAV (wingspan: 20'4", weight: 450lbs) and the C-130 (wingspan: 130', weight: 83,000+ lbs.) the outcome could have been catastrophic. It is important to note that the RQ-7 is a relatively small UAV compared to most other long distance UAVs; many of the military drones being proposed for use in the NAS are closer in size to manned size aircraft. Aside from this incident, over 100 other incidents or accidents involving UASs have been experienced globally, and this figure continues to rise (Drone Wars UK, 2013). The majority of these UASs were US Military and/or US manufactured, and most incidents and accidents resulted from mechanical failure or loss of signal events. Such occurrences set the stage for a great debate on the safety of drone use in domestic airspace and raise important questions about the feasibility of successful UAS integration into the NAS.

Another major challenge facing UAS integration is their unavoidable interaction with the most numerous pilot type in our NAS, General Aviation (GA) pilots. GA is entirely comprised of civil aviation operations, as opposed to scheduled air services and non-scheduled air transport operations. GA flights include everything from single engine trainer aircraft to small corporate jets. As of March 2011, the number of GA certificated pilots in the US was 339,127, more than any other pilot type out of the total US pilot population of 627,588. Of those GA pilots, 119,119 of them were student pilots who were learning to fly and had very little experience (Aircraft Owners and Pilots Association, 2011). The integration of UAS into the NAS poses a great threat to GA pilots, particularly to the student pilots still learning how to fly. This is due to the current approach for preventing mid-air collisions, which is largely based on a see-and-avoid strategy in the GA domain.

The currently implemented tiers of collision protection include radar, which has been in place for decades. Radar essentially provides a bird's-eye-view of surrounding airspace that allows for conflicts to been seen and predicted before they occur, allowing pilots to take collision avoidance action if necessary. Aside from radar, there are also mandated separation minimums, such as the 1,000ft vertical separation for IFR en route traffic that was created so even if one cannot see a potential threat, the buffer of space in-between aircraft will help prevent collisions (granted the aircraft involved are following FAA regulations). Finally, there is also aircraft mounted collision avoidance equipment such as the Traffic Collision Avoidance System (TCAS II) that provides traffic or resolution advisories that command pilots to maneuver out of the predicted path of other

TCAS II enabled aircraft. The problem is, TCAS II is expensive and not installed on most GA aircraft, especially not on student aircraft. Also, radar is only effective if humans are cognitively aware of how to use it and what to do when a conflict is detected (Goyer, 2012). The result is that see-and-avoid strategies are still very much in effect for proper collision avoidance, and it is very difficult to translate this type of strategy to an automated system in the event of a link-loss. Aside from all of these technological challenges that face the integration of UASs into the NAS, challenges are compounded by another complex but highly imperative factor, the Human Factor.

UAS Human Factors Challenges

Human Factors has a, "broad remit, covering all manner of analysis from human interaction with devices, to the design of tools and machines… and various other general aspects of work and organizational design" (Stanton, Salmon, Walker, Baber, & Jenkins, 2005). With regard to aviation, and particularly with the control of UASs, many human factors issues can arise. Most UASs involve a ground control station (GCS) with an operator, or UAS pilot, interacting with displays presenting different flight parameters and current conditions of the UAS. One of the big challenges is successfully controlling UASs remotely, which includes tasks such as mapping, camera view management, and multiple vehicle operations and interfaces. Humans can certainly navigate through natural environments with ease, and this is mainly due to the sophisticated capabilities of our perceptual mechanisms such as our visual, cognitive, and motor processes. While controlling remote vehicles through unfamiliar/unnatural environments, restrictions of available visual information, and limitations in perceptual modality, as well as constraints of physiological motor movement all result in extreme discontinuities experienced by operators in terms of their perception and comprehension of remote spatial information. The perceptual issues in controlling UAS through limited GCS displays are so widely accepted in the aviation and human factors community that GCS displays have been dubbed “soda straw” displays because they limit the operator’s view of the world severely, congruent to navigating only being able to look though a soda straw. Additionally, research has shown that there are a great deal of individual differences in the processing of spatial information , use of wide angle camera views, as well as specific impacts associated with multiple vehicles (Cooke, 2006). This presents a tremendous challenge to the proper design of UAS GCSs.

At present, the general methodology for developing and incorporating UAS technologies into the NAS involves taking current regulations regarding vital flight rules and parameters for current manned aircraft, such as safe operating distances (i.e. separation assurance), up-to-date regulatory requirements, and even emergency procedures, then engineering proper algorithms and intelligence logic for unmanned technologies to encompass the aforementioned parameters. From a human factors perspective, once it is understood how this process of translating current regulation of manned aircraft to unmanned systems works, the proper framework for UAS development can be designed to abide by the above mentioned parameters both manually through the UAS pilot's GCS, and autonomously in the event of a loss of signal (LOS). In this methodology, there remain many challenges to be overcome in order to successfully transfer what has been up to this point mostly human generated skill, judgment, and knowledge in manned aircraft over to the UAS platforms. One particularly challenging area of this manned to unmanned conversion is the concept of "Well Clear".

The Issue at Hand - Well Clear

The term "Well Clear" originated as a phrase used in Air Traffic Control (ATC) environment when interacting with manned aircraft over the radio communications. Typically, a controller will issue an alert to pilots over the radio that nearby traffic has the possibility of breaching legal separation, or may come close to doing so. After notifying pilots of such possible incursions, ATC will then ask them to report once they are "Clear" (i.e., "Well Clear") from the aircraft that posed a collision concern. There are currently no regulated time- or distance-based standards regarding what it means for two aircraft to be 'well clear'." (Lee, Park, Johnson, & Mueller, 2013, p. 1). Due to the highly dynamic and ever-changing flight environment of the NAS, pilots are left on their own to determine when and where they feel this "Well Clear" boundary exists, and they must rely on their own skills and senses in reporting once they believe a collision is no longer possible with the intruding aircraft indicated by ATC. Because there is a lack of an objective definition for "Well Clear", otherwise referred to as the "Well

Clear Boundary" (WCB), and because there is wide variability in human perception across pilots (Cooke, 2006), it is highly likely that different pilots have different opinions of what the well clear boundary is since it is currently entirely subjective in meaning. Additionally, there are also several similar, yet different conceptions to the WCB that pilots may use in determining the term's definition.

Similar Terms and Concepts. Since no regulation for the definition of the WCB exists, it is conceivable that pilots may use alternate similar, however different concepts to help form their mental model of the WCB. Such similar concepts include Lateral Separation Minima, Self-Visual Separation Procedures, and Collision Avoidance Procedures. Lateral Separation Minima are federal regulations in the Federal Aviation Regulations (FARs) governing the horizontal distance planes are required to maintain from each other. The FARs for Instrument Federal Regulations (IFRs), are rules pilots must follow under meteorological conditions that result in poor visibility and necessitate flight navigation primarily by flight instruments. They require a 3 mile horizontal and 1,000 feet vertical separation. FARs for Visual Flight Regulations (VFRs), the rules for pilots flying in visibly clear meteorological flying conditions, state that between VFR and IFR, as well as between VFR and other VFR aircraft must separate themselves based on traffic advisories and safety alerts (issued by ATC over the radios). In en route airspace, these safety alerts are normally given when aircraft fly within 3-5 miles of each other, depending on their trajectories and speeds (FAA, 2014). This is different from Well Clear because it enforces measurable distances to maintain for IFR aircraft, and heavily depends on ATC for VFR aircraft.

Self-Visual Separation Procedures, otherwise known as See and Avoid, more typically occur in terminal airspace. These procedures are used when ATC instructs a pilot to follow another aircraft in an arrival sequence once the pilot confirms that the leading aircraft is in sight. Then, they require the pilot to maintain vigilance in constant visual surveillance of the leading aircraft and not pass it until it is no longer a factor. This form of pilot self-spacing relies solely on out-the-window (OTW) sightings and is therefore limited to use in good visibility conditions. Self-Visual Separation can also incorporate right-of-way compliant maneuvers as well. Self-Visual Separation is different from Well Clear as it is purely based on visual contact after confirmed ATC separation has occurred (FAA, 2005).

Additionally, there are Collision Avoidance Procedures all pilots must follow. These include adhering to all clearances and regulations in the FARs as well as various sources of information attempting to advise pilots on proper avoidance procedures. These sources include FAR 91.113 (b), “Regardless of … IFR or VFR … all pilots will observe “See and Avoid” procedures. There is also an Advisory Circular that has not been updated since the early 1980’s, AC 90-48C entitled “Pilots role in collision avoidance” (FAA, 1983) that outlines various effective visual clearing and scanning procedures for see and avoid. These scanning techniques are further described in the Airman’s Information Manual

(AIM) section 4-4-13(d), and the helpful FAA Library article entitled, “How to Avoid a Mid Air Collision - P-8740-51.” (FAA, n.d.) Additionally, more recent flight safety programs and commercial flight operations have used Traffic Collision Avoidance Systems (TCAS) and/or a Cockpit Display of Traffic Information (CDTI) to help pilots avoid collision. These Collision Avoidance Procedures are different from Well Clear since they are defined in a number of different locations spanning different time periods and they use different forms of collision avoidance assurance.

Proposed Well Clear Definitions and Values. At the time the current thesis began, there were no accepted time or distance-based standards for the definition of the WCB or what it means for an aircraft to remain “well clear.” During the final phases of the present research, a special committee for aviation standards organization, the Radio Technical Commission for Aeronautics (RTCA SC 228), has since settled on an accepted definition which is explained at the end of this section. Before this agreement for the WCB definition was reached, there were several debated methods of measuring safe separation thresholds to apply to UAS automated separation standards. These proposed WCB definitions are described in-depth in the closely related research articles entitled, *“Investigating the Effects of “Well Clear” Definitions on UAS Sense-And-Avoid Operations”* (Lee, Park, Johnson, & Mueller, 2013), “*Establishing a Risk-Based Separation Standard for Unmanned Aircraft Self Separation”* (Weibel, Edwards, & Fernandes, June, 2011), and in SC 228’s consideration material (Cook &

Davis, 2013). These sources include three suggested definitions to close the WCB knowledge gap.

The first considers distance to closest point of approach (CPA) between two aircraft, combined with time to CPA in order to calculate a CPA boundary. As can be seen in the figure below there is a declaration time assigned to intruding aircraft and a time to CPA (tCPA) boundary is generated in the shape of an ellipsoid whose broad side is parallel with ownship trajectory, which equates to a tCPA boundary. This is depicted in Figure 1 below:

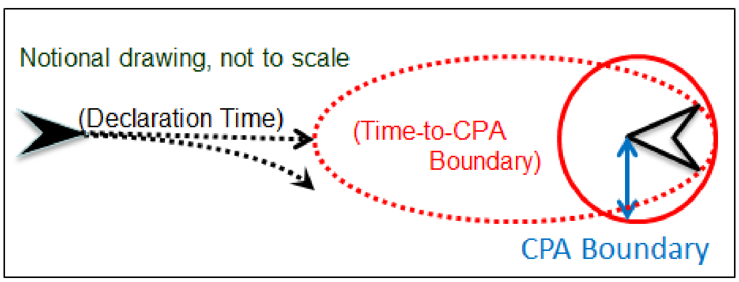

Figure 1. Proposed WCB Definition - CPA and tCPA (Cook & Davis, 2013). Reprinted with permission.

The second proposed definition is a computational method defined by a distance value known as Tau + Distance modification + Horizontal Miss Distance. Here, two types of Tau Range, Tau (τ_{range}) and Vertical Tau (τ_{vert}), are combined to give a value. Range Tau is calculated as a ratio of range between aircraft (r), to their range rate ($\dot{r}$) which is expressed in seconds:

$$\tau_{\text{range}} = -\frac{r}{\dot{r}}$$

Range Tau's counterpart, Vertical Tau, is calculated as the ratio of altitude separation (Δh), to the vertical closure rate ($\dot{h}$) and is also expressed in seconds:

$$\tau_{\text{vert}} = -\frac{\Delta h}{\dot{h}}$$

When combined, these Tau values amount to a positive numerical value when intruders converge with a UAS, and a negative value upon their divergence, representing an approximation of time to CPA or tCPA. However, this equation only works in the case of a direct collision course with a straight line of intersection. This Tau concept can be visualized below in Figure 2:

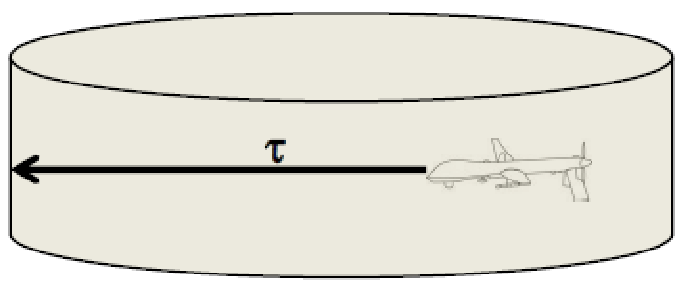

Figure 2. Proposed WCB Definition - Tau and Modified Tau (Cook & Davis, 2013). Reprinted with permission.

The third proposed definition is referred to as the "Ellipsoid defined by Tau with tapered vertical separation." Whereas the previous two definitions can cause issues when two aircraft are encountering each other very quickly (due to alerts being generated far beyond the range of required action by the pilot as a result of the nature of their equations), this ellipsoid uses a tapered vertical separation to avoid "nuisance" alerts resulting from intercepting aircraft that may have enough vertical separation to properly evade each other, but still cause alerts to arise on displays. In other words, it provides a type of filter similar to TCAS II that removes alerts for encounters that will pass more than approximately 1.1nmi apart. This is depicted below in Figure 3:

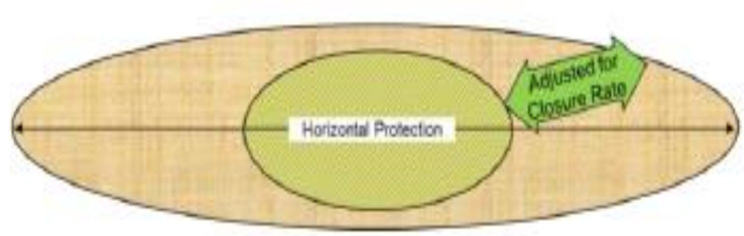

Figure 3. Proposed WCB Definition - Ellipsoid defined by Tau with Tapered Vertical Separation (Cook & Davis, 2013). Reprinted with permission.

Previous research conducted at MIT Lincoln Labs has attempted to simulate the WCB in a brute force mathematical model. Their uncorrelated encounter model was used to generate millions of statistically representative encounters at distances of 3nmi in a Monte Carlo fast-time simulation environment. This model was created with one year's worth of continuous radar data from the continental US, and with it they captured the behavior of VFR air traffic in ten million complementary pairs of aircraft trajectories. Their results gave the following contours of conditional near mid-air collision (NMAC) risk in the horizontal plane, as seen in Figure 4 below:

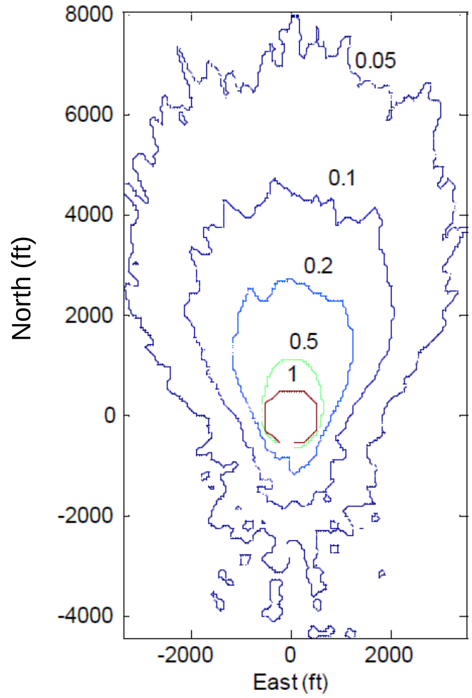

Figure 4. Proposed WCB Definition - Conditional Probability of NMAC (Weibel, Edwards, & Fernandes, June, 2011). Reprinted with permission.

Here, each contour indicates the conditional probability of NMAC, and NMAC risk contours of 1, 0.5, 0.2, 0.1, and 0.05 are shown (Note - there is a probability of 1 that an aircraft is an NMAC within the 500 ft. horizontal boundary defining an NMAC and risk decreases as range from the aircraft increases). Clearly, the asymmetric collision risk contours for likelihoods below 0.5 suggest that conflicts that occur less frequently are dominated by traffic approaching head-on. This can be observed as the NMAC contours widen and spread out much further from ownship towards the front of the aircraft, i.e. head-on as their probability decreases to 0.05. There are also very few overtaking conflicts evident in their simulation analysis. This research suggests the WCB is generally represented by the results of their simulation, and the WCB should be defined according to their contours (Weibel, Edwards, & Fernandes, June, 2011). This MIT Lincoln Labs WCB explanation was eventually voted upon by SC 228 to become the current accepted definition for WCB. However, their "simulation encounter models were built from radar-surveyed performance of existing aircraft under the current structure of the NAS" (Weibel, Edwards, & Fernandes, June, 2011), ignoring concepts of future NAS structure and also only consider manned aircraft encounters with other manned aircraft.

Taking these proposed definitions in mind, several recent FAA sponsored workshops have provided the following description of Well Clear; "*Well Clear is the state of being able to maintain a safe distance from other aircraft so as not to cause the initiation of a collision avoidance maneuver"* (Lee, Park, Johnson, & Mueller, 2013). This definition is a step closer to the goal of providing a discrete value to what the WCB is and how to measure it. However, this definition can still be extremely subjective in any practical sense. It is likely that pilot perception of WCB is different across pilot types due to various skill levels. It is also possible that pilot perception of the WCB with regards to a manned aircraft is different than their perception of WCB from an unmanned vehicle due to various parameters such as size and speed differences, as well as trust in automation and/or new technology that has not met to test of time. The current research aimed to uncover these differences, if any, and also to determine if UAS aircraft are perceived and/or trusted at different levels than manned aircraft. If there is indeed a difference in the perceived WCB between manned and unmanned vehicles, then this difference will likely be intensely measured and researched in order to be integrated in future UAS transition into the NAS.

Purpose

The purpose of this experiment was to explore and measure perceptions of “Well Clear” boundaries for both General Aviation and Commercial pilots, and to investigate any differences in these perceived boundaries between manned and unmanned vehicles operating in the NAS. As mentioned, a recent FAA sponsored Sense and Avoid (SAA) Workshop defined well clear as *“The state of being able to maintain a safe distance from other aircraft so as not to cause the initiation of a collision avoidance maneuver.”* (Lee, Park, Johnson, & Mueller, 2013). Aside from this ambiguous definition, it is also unknown whether there are differences in the perception of well clear boundaries between different pilot types, or between manned and unmanned intruders (aircraft on intercept course with a pilot’s ownship). Additionally, it is presently unknown what elements of the flight environment may have influence on one’s perception of the WCB. The future goal of successfully integrating UAS into the NAS will require an absolute definition of well clear in order to safely develop SAA algorithms intelligent enough to maintain safe operating distances from other aircraft in a manner that makes current manned aircraft feel safe. The current study attempted to provide insight into this absolute definition by measuring and creating a model of the perceived WCB aggregated from participants' performance, all captured quantitatively from a part task simulator environment as well as qualitatively through extensive subjective feedback. With many forms of UASs proposed to operate in all domains of the current NAS, it is vital that any differences in WCB perception between pilot populations and between manned versus unmanned aircraft be determined early in the developmental process in order to design systems as safely as possible.

Safety. Safety is the FAA's top priority, as the FAA currently governs the world's safest aviation system. When faced with the task of safely introducing UASs into the NAS, they openly admit it is quite a challenging issue. They claim that, "Safe integration of UAS involves gaining a better understanding of operational issues, such as training requirements, operational specifications and technology considerations." (FAA, 2014). In addition to the UAS technological challenges mentioned in previous background sections of this research, The Washington Post launched an investigation into drone crash accidents. They discovered that the number of drone accidents is disproportionately high relative to manned aircraft. Since 2001, drones have been involved in more than 400 major accidents around the world. Their investigative documents describe a multitude of costly mistakes by remote-control pilots, not only in combat zones overseas, but also in the United States during test and training flights gone wrong (The Washington Post, 2014).

The Washington Post claims, “In April [2014], a 375-pound Army drone crashed next to an elementary-school playground in Pennsylvania, just a few minutes after students went home for the day. In Upstate New York, the Air Force still cannot find a Reaper that has been missing since November, when it plunged into Lake Ontario. In June 2012, a Navy RQ-4 surveillance drone with a wingspan as wide as a Boeing 757′s nose-dived into Maryland’s Eastern Shore, igniting a wildfire.” According to their investigation, the above crashes resulted from issues such as pilot error, mechanical defects, unreliable communication links; one of the biggest concerns was the limited ability to detect and avoid trouble. “Cameras and high-tech sensors on a drone cannot fully replace a pilot’s eyes and ears and nose in the cockpit. Most remotely controlled planes are not equipped with radar or anti-collision systems designed to prevent midair disasters” (The Washington Post, 2014).

The present research aimed to help gain higher understanding currently needed by the FAA to provide safer integration of UASs into our airspace. By collecting empirical data, it is the goal of this research to help better develop more intelligent UAS systems that will bring new sensing algorithms and successful avoidance techniques from other aircraft through understanding how humans perceive and treat them in the skies. By uncovering information of pilot perceptions concerning how close they will comfortably operate to UASs in current airspace and conveying that information to engineers, the goal is to help design efficient sense-and-avoid technologies to keep manned aircraft safe from UASs in the NAS.

Efficiency. Aside from safety, the FAA also prides itself on creating and maintaining the most efficient aerospace system in the world. As mentioned, the projected increase in aviation traffic and the integration of new UAS technology into the NAS will create a strong need for extremely efficient airspace spacing and operating procedures. Along with the upgrade to NextGen systems, UASs need to follow the same course of efficiency in order to properly mesh with our new aviation environment. Due to the very nature of UAS and their intelligent flight software, they have the potential to fly more efficiently than humans in terms of fuel consumption and direct flight paths, and are not subject to the same limitations humans experience in terms of g-forces, fatigue, and risk of human life. This research will assist in determining how to incorporate the flight paths of UASs into the NAS efficiently by measuring perceived safe operating distances by manned pilots, while maintaining efficient flight parameters throughout all UAS operations by planning accordingly based off this safe operating distance.

Methods

Participants

A total of 34 participants between the ages of 21 and 69 with a mean age of 41 were recruited through the San José State University Research Foundation's (SJSURF) Test Subject Recruitment Office at the NASA Ames Research Center. The participants consisted of 3 females and 31 males. Collectively, the pilots had a total of 173,405 flight hours, with a total of 78,325 of those hours spent in glass cockpits (cockpits with screen displays instead of purely gauges to present avionics information). This led to an average of 5,100 total flight hours, with an average of 2,373 of those hours being in glass cockpits per pilot. In terms of years of experience flying, this study averaged 20 years of flight across each pilot.

Participants were required to be licensed pilots. The experimental design for this study is explained in the following section. Because examining differences between pilot types involved a direct comparison, an equal number of General Aviation (GA) and Commercial/ATP (Airline Transport Pilot) pilots was selected, with 17 of each type of pilot. The Commercial/ATP pilots averaged 48 years of age with 28 years of flying experience. They also averaged 9,627 flight hours, averaging 4,533 in glass cockpits. The GA pilots had a mean age of 34, averaging 13 years of flying experience. They averaged 573 flight hours, with a mean of 79 hours in glass cockpits.

Aside from having a valid FAA Pilots License for their particular pilot group (more experienced ATP and less experienced GA pilots), no other experience requirements were necessary. Participants with both regular and corrected vision (glasses or contact lenses) were recruited, as long as their vision was concordant with current FARs regarding vision proficiency. All participants were compensated for their efforts.

Experimental Design

The current study used a mixed design; there were several within-subject variables with pilot type as a between-subjects variable. In order to assess differences in WCB perception across the two different pilot types, a five-factor mixed design was implemented. The between-subjects variable of pilot type was the comparison of highest interest in the current study, as it sheds light on potential differences in WCB between pilots of different experience levels. Interest in the comparison of pilot type was closely followed by the interest in comparison of intruder type, which varied between manned and unmanned aircraft throughout the experimental scenarios. This variable allowed us to observe any differences arising from manned pilots interacting with other manned versus unmanned aircraft, an important factor in designing the future parameters of our airspace and successfully integrating UASs into the NAS.

To determine what affects the WCB perception for pilots in the NAS, four independent variables were compared across both pilot groups. These repeated measures factors were; intruder type (2 levels), intruder aircraft approach geometry (8 levels), background distractor traffic (2 levels: high and low), and ownship speed (2 levels). As previously mentioned, the between groups variable of pilot type was used in this mixed design, which had two levels as well. The two levels of intruder aircraft type were used to uncover if pilots had differences in their opinion of the well clear boundary when interacting with manned vs. unmanned intruding aircraft in the NAS. Approach geometries were designed to be from 8 different directions surrounding ownship to examine the WCB from different approach angles. The study by Weibel et al. (2011) cited earlier suggests an important role for approach geometry in the definition of WCB. The final two independent variables of background traffic level and ownship speed. Each had two levels and was used to see if those parameters of the flight environment affected the perception of the WCB. Altogether, this yielded an 8x2x2x2x2 design. In order to control for any order and/or learning effects resulting from the factorial combination of the four within-subjects variables, presentation of all combinations were randomized for all participants. These independent variables are discussed in the section below entitled “Stimuli”.

Due to the constraints of limited pilot availability and research resources, the researcher was unable to provide a participant pool large enough to likely yield significant results in the comparison of pilot type. Proper statistical significance would not likely be present without a pilot sample population size of at approximately 240+ participants (as determined through statistical software) and simply was not feasible in this research setting. Therefore, it must be noted that all findings for the between-groups variable of pilot types may suffer from a low statistical power. However, this research highlights general findings for a decent sample size that can be used as future research framework, and sheds important light on the unknown subjective and objective pilot definition of WCB.

Apparatus

The testing took place in the Flight Deck Display Research Lab (FDDRL) at NASA Ames Research Center located in Moffett Field, California. The FDDRL-developed Cockpit Situational Display (CSD) was used as the primary display for this research. The CSD was designed for FDDRL's advanced Cockpit Display of Traffic Information (CDTI) experimental needs, and is configurable to display simple and advanced interfaces. For this research, the CSD was configured in a simple, 2D top down view mode with conflict detection, flight path predictors, weather mapping, and route re-planning disabled to create a bare bones display similar to present day traffic collision avoidance systems (TCAS). The CSD was displayed on a desktop computer running the Windows 7 operating system. The computer had an Intel Core i7-2600K Sandy Bridge 3.4GHz processor, 8GB of DDR3 1600 RAM, utilizing an ASUS P8P67EVO Motherboard, with a Western Digital 1TB HDD (7200rpm, 64MB Cache, 6GB/s), and a GIGABYTE GeForce GTX 460 video card that had a Dell 3007WFP supporting resolution of 2560x1600 or better. The computer monitor used measured 19" diagonally and had a 4:3 aspect ratio full color flat screen LCD display. Participants were also recorded during the open discussion they had with the researcher at the end of the study in order to properly review their subjective feedback. No other form of recording or photography took place. For scenario development, the NASA Ames-made Multi Aircraft Control Simulator (MACS) software was utilized to create conflicts and manage the interaction of aircraft in a high-fidelity simulation of local northern California airspace.

Stimuli

Simulator Experimental Environment. The environment in the Multi-Aircraft Control Simulator (MACS) was modeled after real-world air traffic controlled airspace of sectors 40 and 41, centered over the Santa Rosa airport in northern California. No out-the-window view was provided, the only display available was the Cockpit Situational Display (CSD), which essentially served as a Cockpit Display of Traffic Information (CDTI) with a 2-dimensional simplified top-down view of the environment surrounding ownship. Flight conditions were nominal, with no wind or other weather involved. There were no active air traffic controllers speaking with or directing pilots, as pilots had no control over their aircraft's pre-designated flight path and were only flying in the airspace for a couple of minutes at a time.

Pilots viewed the CSD display with their ownship at the center of the traffic display. In the MACS environment, there were two types of traffic flying in the airspace surrounding ownship, consisting of both distractor traffic and intruder traffic. Distractor traffic served the purpose of simulating a regularly-crowded airspace typically encountered in routine flights. They were not meant to negatively impact participants' attention, but served to recreate normal traffic levels that any pilot is likely to experience. The flight path of all distractor traffic was designed fly at altitudes different than ownship, so as not to cause any conflicts or be confused with intruder traffic. The intruder traffic was of primary interest in this research, and there was only one of them displayed on the CSD per scenario. The single intruder varied between being a manned or unmanned aircraft (indicated by "NASA11" for manned, and "UAS11" for UAS in their data tags next to aircraft icon on CSD) per scenario as well. The intruder was on a straight and level course that would eventually violate legal separation, and was always set to be on a collision course with ownship. See example in Figure 5.

It is important to note that while observing the CSD, pilots had control over range zoom on the display and had the ability to change zoom levels at will. On current day traffic and moving map displays, the ability to change range via the flick of a knob or button press is standard, as different scenarios call for different range views. Pilots dynamically switch ranges to observe different factors of their current flight environment, so they were allowed to do this freely in the simulator environment. The range rings surrounded ownship position, moving and re-centering along as the map moved below ownship. They were displayed as circles of light grey tint across the black background of the CSD, and can be seen in Figure 5 below.

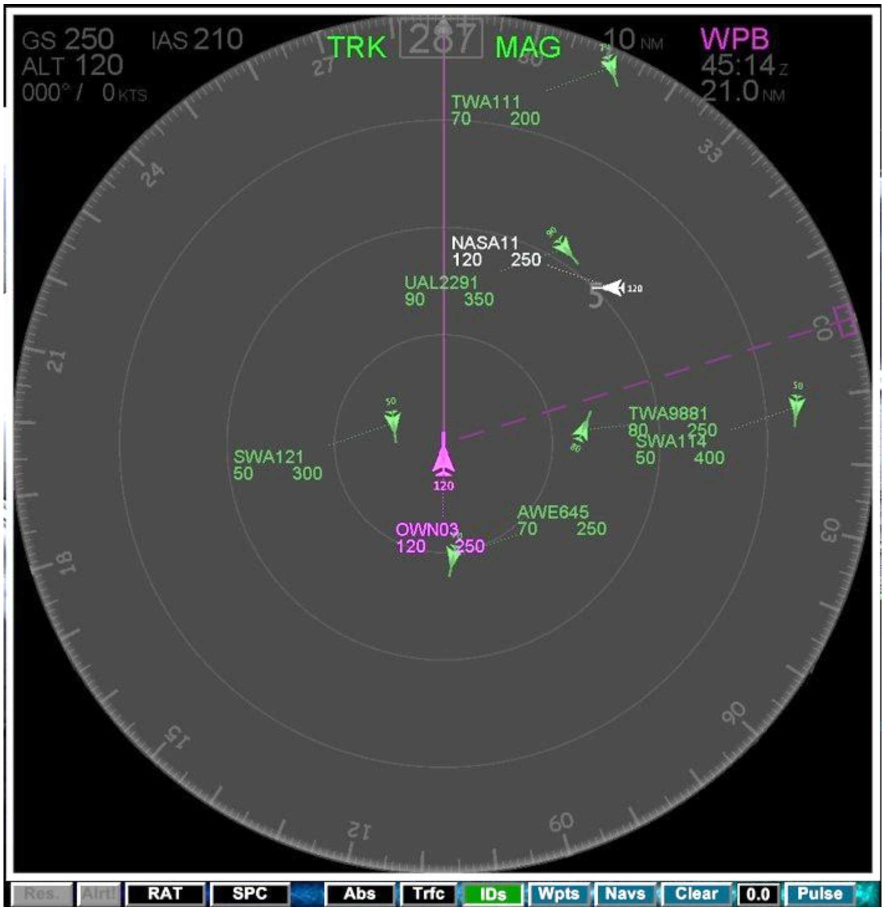

Figure 5: Cockpit Situational Display in simple 2D mode (Alerts Disabled)

Intruder Approach Geometry Levels. The approach geometries of intruder aircraft were of particular interest in this study. This independent variable involved intruder aircraft, which varied from being either manned or unmanned as counterbalanced throughout scenarios. Intruder aircraft differed from distractor traffic in that there was only one intruder aircraft per scenario, and the intruder was always aimed at the participant's ownship and would imminently cause a collision (or at the very least cause a severe breach of self-separation with ownship). All intruder aircraft were set at co-altitude with ownship. The purpose of the intruder aircraft was to put it on a collision path, then instruct participants to press a button to pause the simulation once they felt the intruder reached the well clear boundary surrounding ownship. Once the simulation was paused, the location of the intruder ship was recorded by the researcher. Participants were told how to identify the difference between a manned and unmanned aircraft on the CSD, as it was depicted with a different icon on the CSD than other traffic. There were eight different approach geometries for the intruder aircraft and it approached from one geometry per scenario. The geometries are shown below in Figure 6, with four geometries approaching from the four cardinal directions (N, S, E, W), and another four set on a 45° offset from the original four, dissecting all four quadrants in half, totaling of eight geometries.

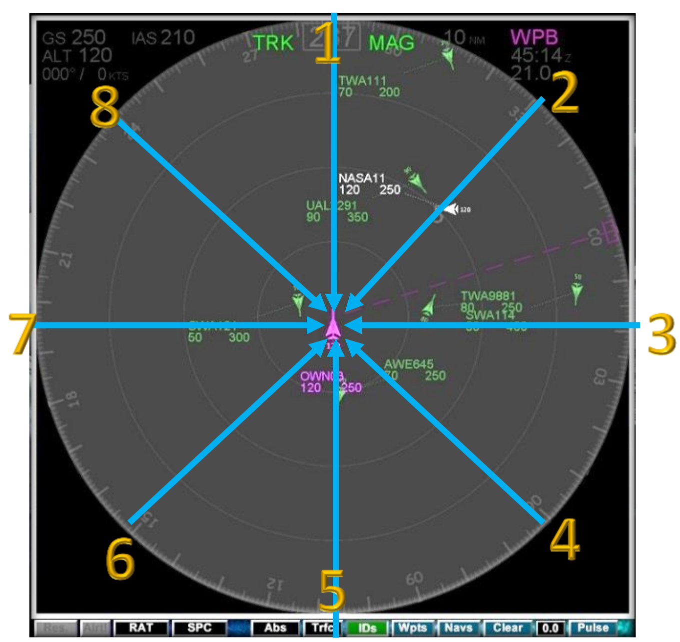

Figure 6: Intruder approach angles depicted on CSD

Distractor Traffic Levels. There were two levels of the distractor traffic variable involved in the scenarios. This air traffic served to create a real-world representation of traffic loads that can be typically experienced in the immediate surrounding airspace of ownship. This traffic was all flown on pre-designated flight plans that were not controlled in real time. These aircraft were all fully simulated in the trials and were placed on straight and level flight paths that would not cause any conflicts with ownship. To accomplish this, all distractor traffic was flown at altitudes at least 2,000 feet above or below ownship, as indicated by their data tags on the display. Depending on the scenario, each trial involved either a low level of distractor traffic consisting of 4 planes, or a medium level of traffic involving 8 planes. These quantities for traffic density were chosen based on previous research conducted with the CSD at NASA Ames, and are typical traffic levels for this type of research (Vu, Strybel, Battiste, & Johnson, 2011; Johnson, Jordan, Liao, & Granada, 2003)

Ownship Speed Levels. Two different levels of the ownship speed independent variable were designed into the scenarios. The goal for this independent variable was to test ownship speeds that represented a realistic middle ground for what speeds the two different pilot types would typically encounter. Because ATP pilots normally fly at much faster speeds than General Aviation pilots, , the high speed selected was 250 knots since this is the maximum speed limit for controlled airspace within the NAS, and it is not inconceivable for GA pilots to reach these speeds (depending on the aircraft they are piloting). For the lower speed, 150 knots was chosen since this is a bit faster than trainer aircraft normally fly, but should be a familiar speed within reach of most GA pilots and their typical aircraft. Different speeds for ownship were chosen in order to investigate if the WCB changes with the speed of ownship, possibly growing at higher speeds since objects in the sky are approaching ownship at much higher rates.

Through the repetitive process of administering intruder aircraft from different approach angles surrounding ownship throughout 64 trials, the goal was to create a picture of the perceived WCB points for each pilot. After recording the perceived boundary points for each pilot, we averaged the boundary points of each pilot type (8 GA pilots averaged across each other, and 8 Commercial pilots averaged across each other, separately) to depict the general WCB as perceived by that pilot type. We also created two different versions of the averaged WCB pictures by intruder aircraft type that is, manned vs. unmanned within each pilot type, to discover if intruder type had any impact on the boundary.

Practice Scenarios. Before data was collected in the experimental scenarios, all pilots had an opportunity to use the CSD through 5 practice scenarios. Although many pilots in this study were well familiar with 2-dimensional traffic displays, these practice trials allowed pilots to better comprehend the unique properties of the CSD (such as directional traffic information and data tags next to traffic icons) allowing for roughly equal experience with the simulator environment. The practice trials also helped eliminate any simulator adaption issues that may have hindered the results of the experimental trials. During practice pilots had constant interaction and feedback from the Researcher, who ensured any questions about the display were thoroughly answered. In the practice trials, pilots were able to view the normal distractor traffic, as well as different scenario recreations with both manned and unmanned intruder aircraft in order to help them correctly differentiate the different icons representing different types of aircraft.

Experimental Scenarios. Once the practice scenarios were complete, the experimental trials began. The data from these scenarios were recorded for analysis. The experimental trials were created to encompass a full factorial design of all combinations of the above mentioned variables (two traffic levels, two ownship speeds, two intruder types, and eight intruder aircraft approach geometries), which yielded 64 different combinations, each of which were tested on each of the 17 participants in the two pilot groups. Conflicts were pre-scripted with the intruder aircraft always designed to be on a conflict/collision course with the straight and level flight path of ownship in every scenario. All scenarios began with ownship traveling at one of the two above mentioned cruise speeds, with distractor traffic and an intruder aircraft flying in surrounding airspace. Intruders were designed to come into conflict with ownship within approximately two minutes for each scenario, yielding quick and easily administered trials. The only objective given to the pilots was to click the right mouse button on the computer running the simulation once an intruder aircraft crossed what they felt was their perceived WCB, and believed the intruder could become problematic if it continued on its current trajectory.

Procedure

After institutional review board approval the experiment took place in a simulator room that was isolated from any distractions. Before beginning, pilots signed an informed consent form, then were briefed about the background of the study and current FAA regulations/definitions of similar concepts to the WCB concept to help differentiate and eliminate possible confusion of terms. Similar concepts to well clear included legal separation, collision avoidance procedures, and self-separation procedures (all previously explained above in the section entitled “Similar Terms and Concepts”). Following the explanations, pilots were then briefed on the best and most recent FAA definition for the concept of well clear. After the pre-simulation brief, pilots had an opportunity to ask questions in order to clarify their understanding of the definitions of the similar concepts. The researcher replied thoroughly with great care given not to contaminate their notion of well clear, emphasizing the subjectivity of its current definition.

After the briefing, pilots were then subjected to a series of trials designed to measure perceived WCBs from both manned and unmanned vehicles using a single display platform. The primary task accomplished by participants was the experimental task. No other tasks such as manual flying or monitoring of any other displays were involved, as this was a part task simulator-based study. Participants viewed the CSD with ownship located at the center of screen, and other aircraft traffic surrounding their current location. Before data collection began, participants first had practice trials that consisted of five scenario runs, each lasting approximately 2 minutes. Again, during these practice runs pilots had the freedom to ask any questions they wished in order to better acclimate themselves to the CSD and the part-task simulator environment.

After the practice runs, all participants went through a series of 64 experimental trials in rapid succession, with appropriate breaks given at the participants' discretion. The researcher controlled the initiation of each trial. The randomized experimental order allowed for a good distribution of exposure order for the different scenarios in this study. Each trial involved either 4 or 8 distractor aircraft that were evenly dispersed around the airspace of ownship, and 1 intruder aircraft showing up from 8 different geometries surrounding ownship (1 geometry per scenario), and the participants ended the scenario with a mouse click once that intruder had breached the WCB. Once each scenario ended, the position of each intruder, along with the distance from CPA, and tCPA were all recorded by the CSD software. Through this repetitive process we were able to create a spatial representation of the averaged WCB directly surrounding ownship by combining the WCB positions of all intruder aircraft for each participant's trials and aggregating the measurement data.

Measures

Objective Metrics. The objective metrics collected in this study were primarily aimed at measuring the WCB as it was perceived by pilots in all scenarios. The intruder aircraft's final recorded position, direction and speed in the simulator were used to calculate the main objective metrics for the perception of well clear. The WCB points were indicated by participants clicking a mouse button when the intruder passed what they considered the WCB, allowing for the intruder's distance from ownship and time until CPA to be calculated in feet (all regarding the horizontal plane distance only). The intruder aircraft approached ownship from eight different geometries surrounding it, and once all of the locations were mapped from all scenarios, an averaged top down view map of perceived WCBs for all intruders was created. Multiple WCB maps were created with the distance in feet metric, one for each variable collapsed across the others, as well as an overall WCB map. In addition to measuring the WCB in distance from ownship (dOWN) in feet, it was also measured in tCPA in seconds. The tCPA for each approach angle was calculated as t (time) = d (distance) ÷ r (rate) with distance the length of last recorded position of the intruder ship to the point where ownship and intruder intersected. The main WCB maps of interest were for the two different pilot types, and for the two different intruder types. The result was an accurate measureable comparative representation of different pilots' perception of the WCB for both UAS and manned aircraft in the NAS.

Subjective Metrics. The subjective metrics utilized were designed to complement the objective metrics, along with providing further insight into the concept of the WCB. During the experimental trials, any significant comments made by the pilots regarding WCB or their perception of it were recorded by the researcher, and were used to supplement the post-experiment questionnaire. There was no post-trial questionnaire administered, since each trial was short, and administering a questionnaire after each trial would be intrusive. After all experimental trials were complete, a post-experiment questionnaire was administered to the participants. It consisted of 15 open-ended, and 5 rating scale questions designed to provide detailed insight about their thoughts and interpretations of the WCB (see Appendix D). A final question asked the pilots to illustrate through drawing a picture what they perceived the WCB to be for both manned and unmanned aircraft surrounding ownship. The drawing questions provided a page with a blank CSD display, with ownship indicated at the center, and range unlabeled range rings were provided. They were asked to not only draw the shape of the WCB, but also indicate the appropriate range on the range rings to more accurately depict their perception. Drawings were done to determine if pilots' perceived WCB matched their actual recorded WCB, another important human factors measure. The drawings were then sorted by common shapes/features and tallied up to summarize findings. This subjective feedback was compared to the objective data described above.

Analysis

The WCB data were analyzed with a five-way mixed ANOVA to analyze differences across all variables and to assess any interactions. For all tests, alpha (significance level) was set to .05.

Results

WCB Maps

The results of all WCB measurements are presented below in the form of maps, with separate maps for the dOWN metric as well as the tCPA measurements. These maps have not been subjected to any form of statistical analysis other than averaging results per intruder approach angle to aggregate mean values. Helping to visualize measurements, multiple maps were created by collapsing data across every independent variable to show the effect each one had on the overall WCB map shape. All maps have ownship heading north (000°). The seemingly inverse relationship between the dOWN and tCPA maps is due to closure rate. Distances are large with small times in front of ownship because closure rate was high, so pilots wanted the most distance because they had the least time to react in a head-on scenario. Distances are small and times are great in the rear because closure rates were small, so pilots allowed small distances due to high time to collision.

Figure 7 below shows the difference in the WCB values across different intruder approach angles and collapsed across all other independent variables, with the head-on angle having over double the value of the rear value for dOWN. The peripherals appear largely uniform with very little variation compared to their horizontal symmetric counterpoint. The tCPA also follows suit, with an inverse relationship in values for head-on and rear directions as explained in the previous paragraph. These maps are cohesive with the logic of closure speed and time/distance needed to safely react throughout different encounter situations.

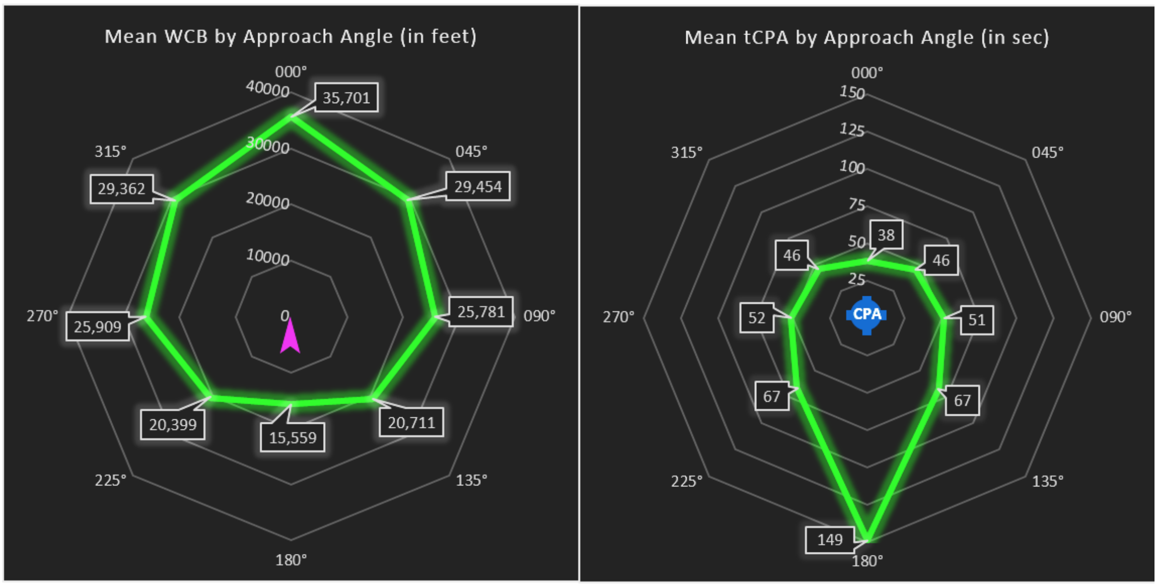

Figure 7. WCB by Direction

The following maps in Figures 8 through 15 are provided to display the effects that each independent variable (IV) had on the WCB (pilot type, ownship speed, intruder type, and traffic levels), collapsing across the effects of all other IVs except approach angle. They visually highlight isolated effects, which may or may not be statistically significant, allowing for good conception of each IV's role in WCB perception. Ignoring all other IVs, Figures 8 and 9 show between pilot type maps, with GA pilots having a much larger WCB than ATP pilots. Each GA pilot data point is several thousand feet greater than the ATP pilot dOWN values.

The tCPA values follow suit, and show the GA pilots having greater values by at least 3 seconds, and as much as 16 seconds difference from ATP pilots.

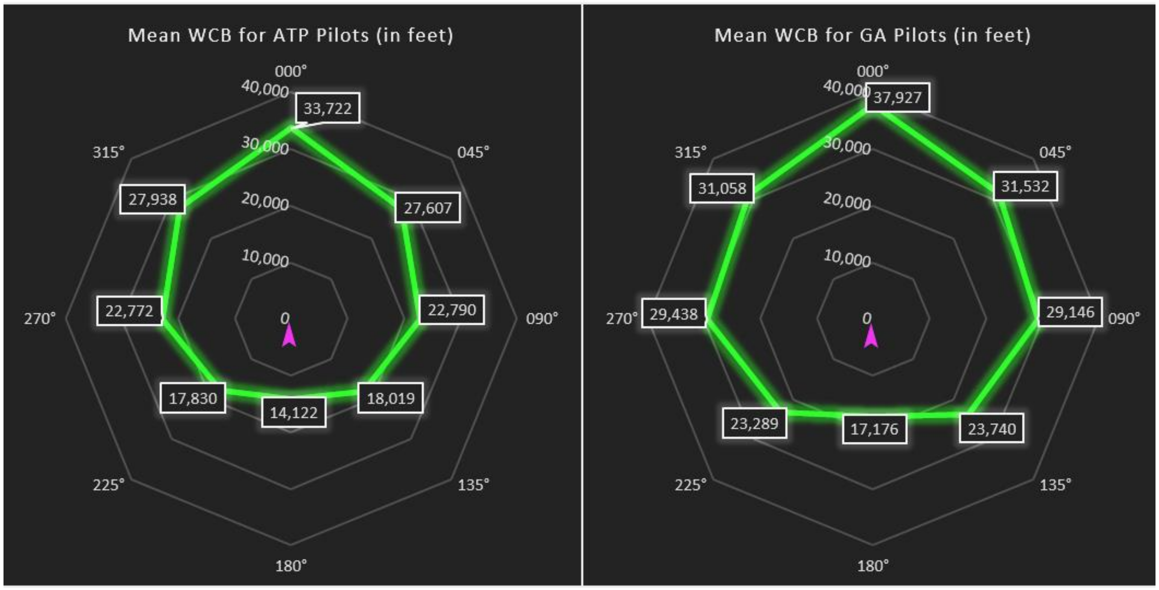

Figure 8. dOWN of WCB by Pilot Type

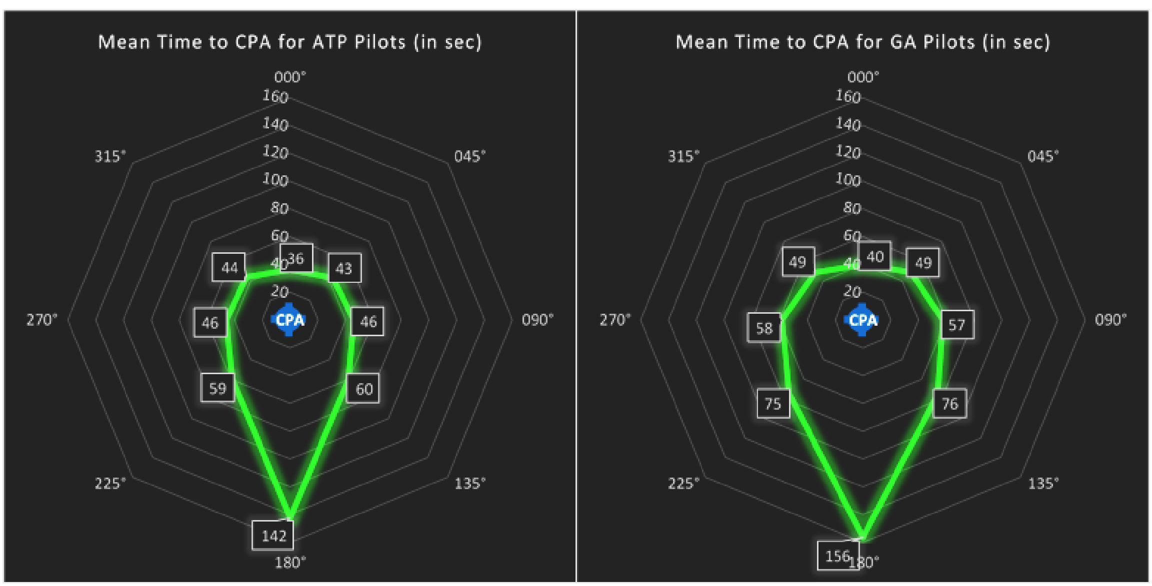

Figure 9. tCPA of WCB by Pilot Type

In Figures 10 and 11, ignoring all other IVs, ownship speed appears to change the values of dOWN measurements slightly, with small increases in the higher speed scenarios. The shape of the 250 knot map is also considerably wider specifically in the 315° and 045° angles (or the forward 45° angles from ownship). Conversely, the tCPA values are all larger on the 150 knot map, except for the head-on angle of 000°, which appeared less in the 150 knot map compared to the 250 knot map. Reasoning for this is provided in the Discussion section.

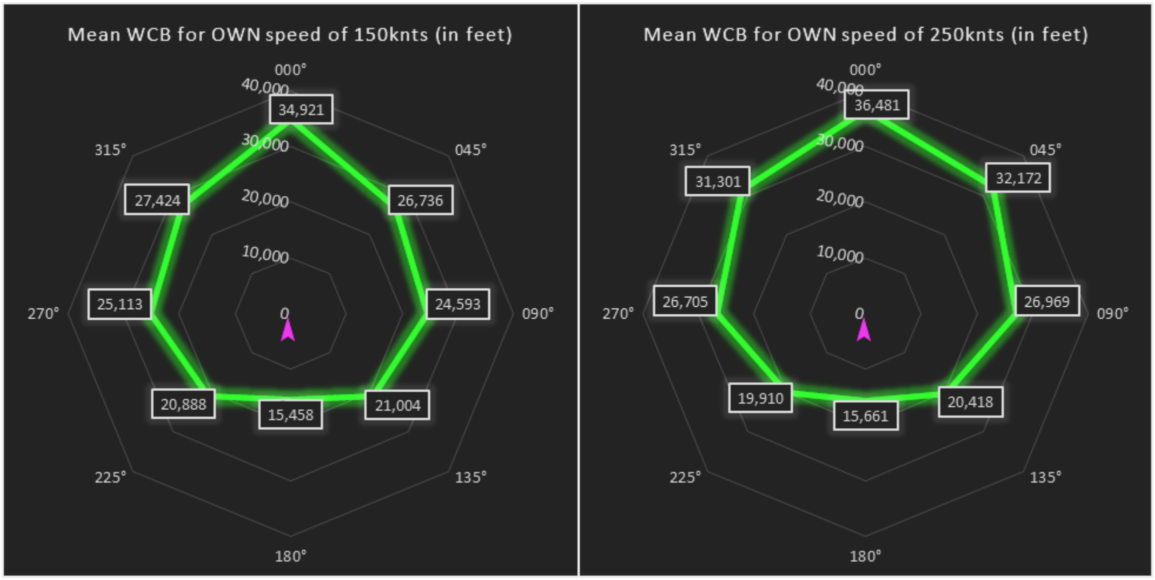

Figure 10. dOWN of WCB by Ownship Speed

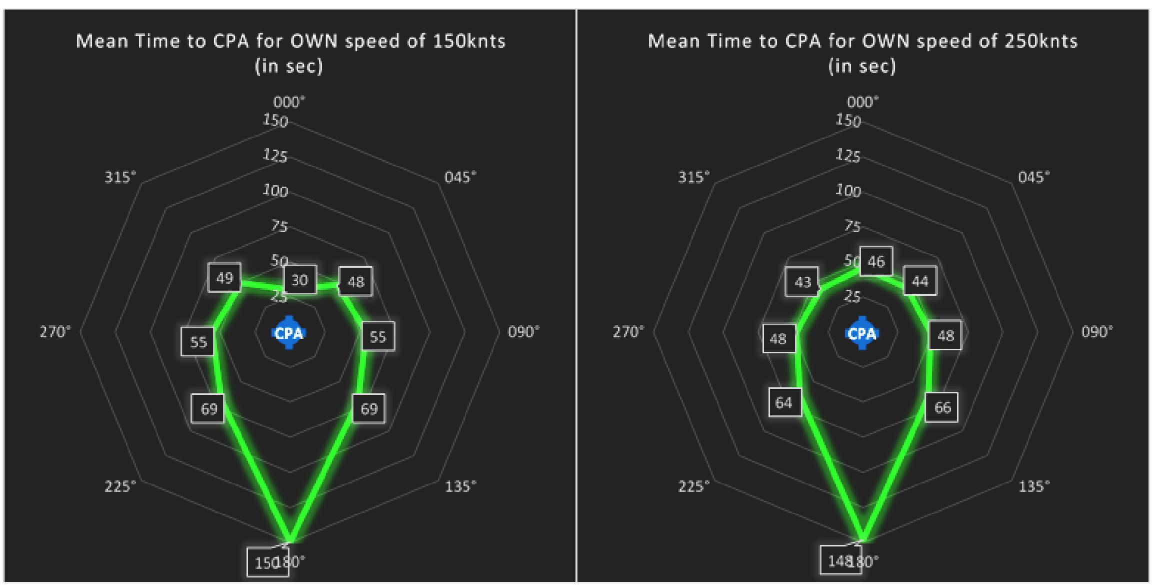

Figure 11. tCPA of WCB by Ownship Speed

In Figures 12 and 13 we can observe interesting results. There appear to be mixed dOWN value differences across intruder types. The manned intruders have slightly larger dOWN values for the head-on and rear approach angles, as well as the 90° and 270° angles than UAS intruders. However, the manned intruders have slightly smaller values for the 315°, 45°, 225°, and 135° angles than UAS. The tCPA values also follow suit here, with nearly identical difference patters.

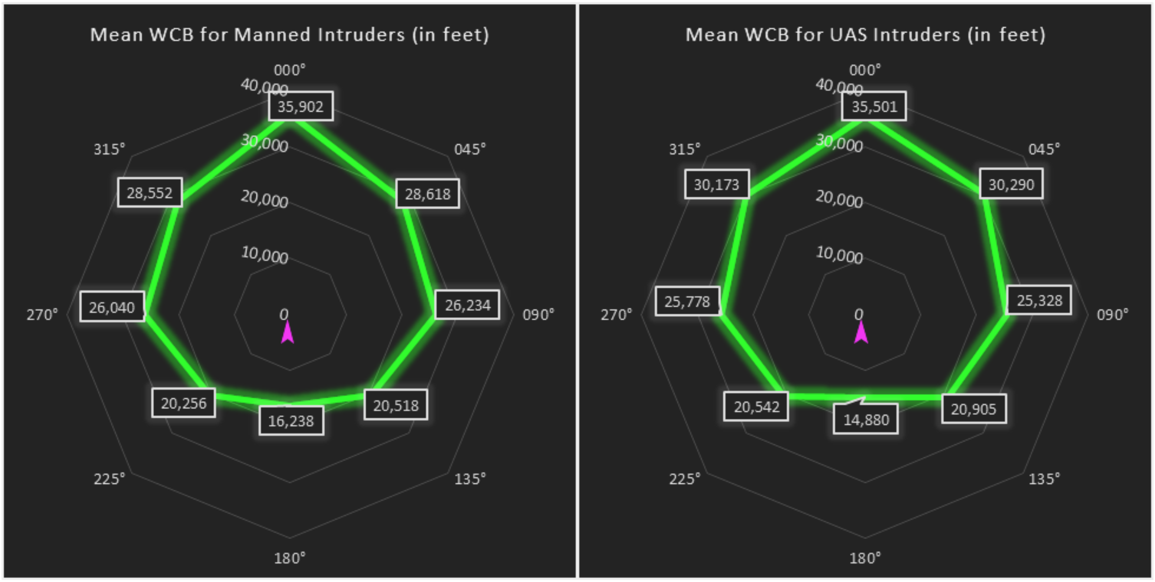

Figure 12. dOWN WCB by Intruder Type

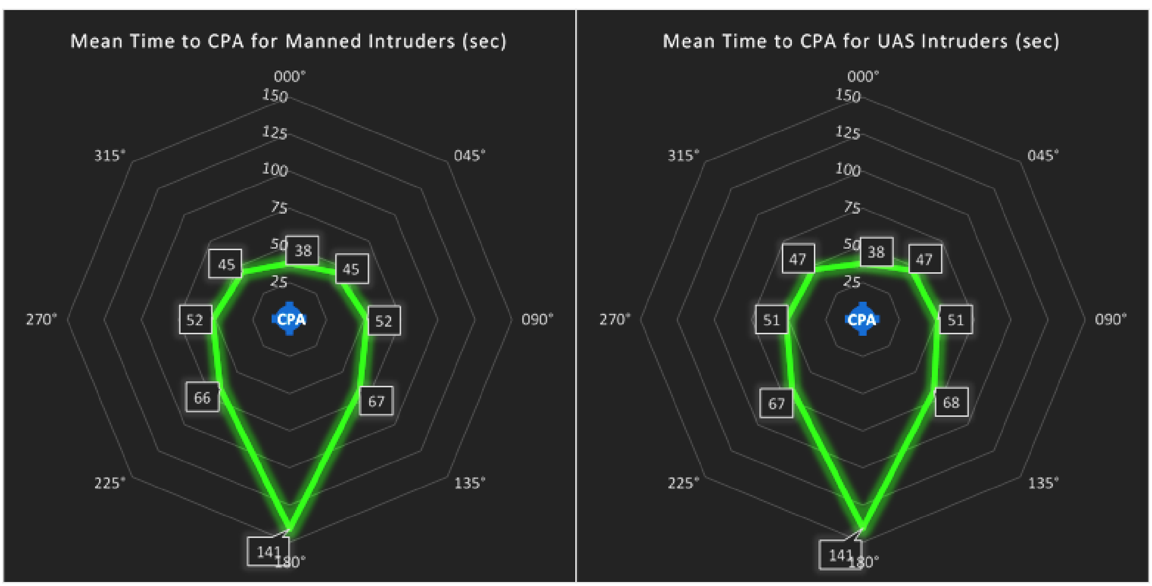

Figure 13. tCPA of WCB by Intruder Type

Below, Figures 14 and 15 show slightly smaller dOWN values in the medium background traffic level (8 background aircraft) than the low traffic level (4 background aircraft) scenarios. The tCPA values followed suit here, but with slightly less noticeable differences. This trend was evident for all angle directions in these maps.

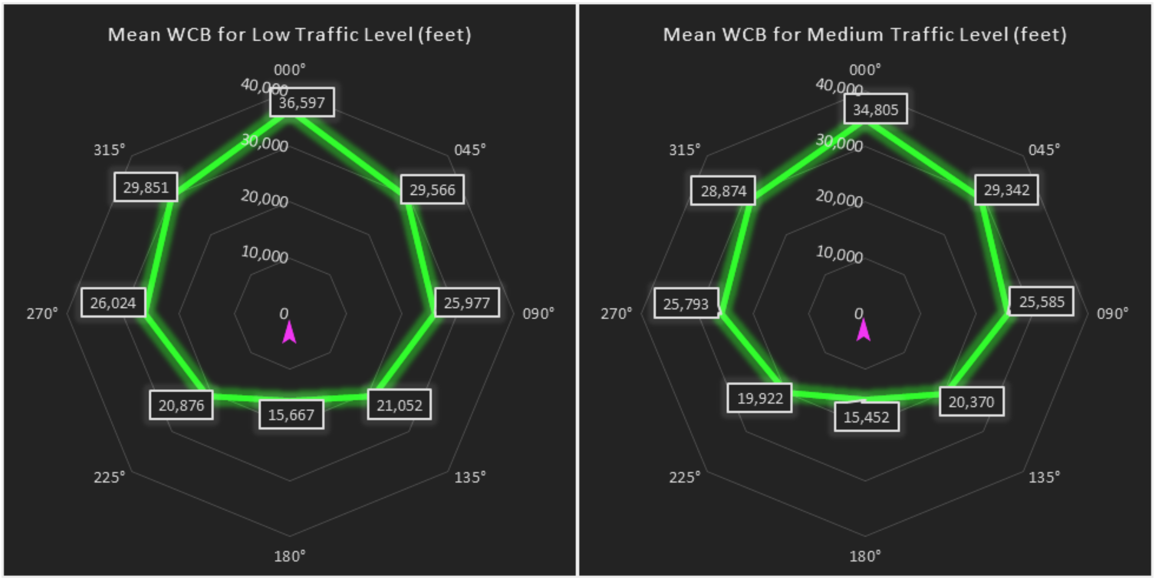

Figure 14. dOWN of WCB by Traffic Level

Figure 15. tCPA of WCB by Traffic Level

Objective Metrics Results

The WCB was measured in two ways to provide a full understanding of its parameters, measured by dOWN in feet, and tCPA in seconds. Therefore, two five-way mixed analyses of variance (ANOVA) were used to analyze these quantitative WCB measures. The five factors in the mixed ANOVAs were the between subjects variable of pilot type and intruder approach angle, intruder type, ownship speed, and traffic level.

Distance from Ownship (dOWN). The first five-way ANOVA was performed on the dOWN measure, which was the distance from ownship in feet indicating the WCB. This consisted of an 8 x 2 x 2 x 2 x 2 ANOVA for significant differences among approach angles, intruder types, ownship speeds, traffic levels, and pilot types. Results found two significant interactions and three main effects. A significant three-way interaction was evident among intruder type, ownship speed, and pilot type, $F(1, 32) = 4.56$, $p = .041$. This indicates that the effect of intruder type depends on ownship speed and that differs across pilot type. A significant two-way interaction was also observed with ownship speed and intruder approach angle, $F(5,175) = 6.85$, $p = .004$. Main effects were also found for intruder approach angle, $F(1, 55) = 27.68$, $p < 0.001$, ownship speed, $F(1, 32) = 9.76$, $p = 0.004$, and traffic level, $F(1, 32) = 5$, $p = 0.045$. Besides these interactions, no other effects for the metric of dOWN in feet were found to be significant. For all dOWN means and standard deviations, as well as full dOWN interaction results, see Tables 1 and 2 below.

Table 1: Means and Standard Deviations for dOWN in feet

Scenario	Pilot Type	Mean	Std. Deviation
Manned Intruder_Low Traffic_150knots_Angle 1	ATP	13752	4347
	GA	17300	15439
	Total	15526	11313
Manned Intruder_Low Traffic_150knots_Angle 2	ATP	17389	7788
	GA	24532	18106
	Total	20960	14195
Manned Intruder_Low Traffic_150knots_Angle 3	ATP	24170	13004
	GA	27453	16515
	Total	25812	14732
Manned Intruder_Low Traffic_150knots_Angle 4	ATP	23269	13642
	GA	29931	17533
	Total	26600	15834
Manned Intruder_Low Traffic_150knots_Angle 5	ATP	35069	25209
	GA	37173	23135
	Total	36121	23849
Manned Intruder_Low Traffic_150knots_Angle 6	ATP	26588	15086
	GA	28761	16694
	Total	27675	15707
Manned Intruder_Low Traffic_150knots_Angle 7	ATP	22944	13716
	GA	29012	16473
	Total	25978	15241
Manned Intruder_Low Traffic_150knots_Angle 8	ATP	18465	8811
	GA	25112	15962
	Total	21789	13136
Manned Intruder_Low Traffic_250knots_Angle 1	ATP	13593	4434
	GA	17935	13557
	Total	15764	10173
Manned Intruder_Low Traffic_250knots_Angle 2	ATP	19068	9729
	GA	22508	12579
	Total	20788	11210
Manned Intruder_Low Traffic_250knots_Angle 3	ATP	23510	14718
	GA	30366	19799
	Total	26938	17527
Manned Intruder_Low Traffic_250knots_Angle 4	ATP	30790	20730
	GA	30803	17245
	Total	30797	18776
Manned Intruder_Low Traffic_250knots_Angle 5	ATP	34710	27162
	GA	39142	24306
	Total	36926	25480
Manned Intruder_Low Traffic_250knots_Angle 6	ATP	29474	21650
	GA	31829	19106
	Total	30652	20141
Manned Intruder_Low Traffic_250knots_Angle 7	ATP	23623	15083
	GA	30070	19594
	Total	26846	17526
Manned Intruder_Low Traffic_250knots_Angle 8	ATP	16665	8272
	GA	22335	12727

	Total	19500	10954
Manned Intruder_Medium Traffic_150knots_Angle 1	ATP	17606	19959
	GA	16700	12591
	Total	17153	16438
Manned Intruder_Medium Traffic_150knots_Angle 2	ATP	18092	9254
	GA	23182	10365
	Total	20637	10014
Manned Intruder_Medium Traffic_150knots_Angle 3	ATP	22061	12871
	GA	26644	15158
	Total	24353	14040
Manned Intruder_Medium Traffic_150knots_Angle 4	ATP	25054	16788
	GA	26527	16598
	Total	25791	16455
Manned Intruder_Medium Traffic_150knots_Angle 5	ATP	34427	25357
	GA	33808	17907
	Total	34117	21617
Manned Intruder_Medium Traffic_150knots_Angle 6	ATP	24865	14726
	GA	28165	18153
	Total	26515	16362
Manned Intruder_Medium Traffic_150knots_Angle 7	ATP	21436	10901
	GA	27267	13723
	Total	24351	12557
Manned Intruder_Medium Traffic_150knots_Angle 8	ATP	17492	7987
	GA	22307	11986
	Total	19899	10322
Manned Intruder_Medium Traffic_250knots_Angle 1	ATP	14771	5696
	GA	18249	13035
	Total	16510	10061
Manned Intruder_Medium Traffic_250knots_Angle 2	ATP	17123	8127
	GA	22247	12606
	Total	19685	10763
Manned Intruder_Medium Traffic_250knots_Angle 3	ATP	24640	17047
	GA	31023	19514
	Total	27831	18331
Manned Intruder_Medium Traffic_250knots_Angle 4	ATP	28275	20025
	GA	34294	19524
	Total	31285	19712
Manned Intruder_Medium Traffic_250knots_Angle 5	ATP	33239	24256
	GA	39645	29035
	Total	36442	26544
Manned Intruder_Medium Traffic_250knots_Angle 6	ATP	28134	16324
	GA	30597	19286
	Total	29366	17638
Manned Intruder_Medium Traffic_250knots_Angle 7	ATP	22547	14175
	GA	31419	17878
	Total	26983	16513
Manned Intruder_Medium Traffic_250knots_Angle 8	ATP	16869	9038
	GA	22801	12814
	Total	19835	11326

UAS Intruder_Low Traffic_150knots_Angle 1	ATP	12642	3214
	GA	17037	13184
	Total	14840	9708
UAS Intruder_Low Traffic_150knots_Angle 2	ATP	18757	9466
	GA	25570	15569
	Total	22163	13150
UAS Intruder_Low Traffic_150knots_Angle 3	ATP	20502	12055
	GA	27616	15682
	Total	24059	14239
UAS Intruder_Low Traffic_150knots_Angle 4	ATP	26234	16800
	GA	28682	18149
	Total	27458	17265
UAS Intruder_Low Traffic_150knots_Angle 5	ATP	32251	24064
	GA	39195	26023
	Total	35723	24930
UAS Intruder_Low Traffic_150knots_Angle 6	ATP	26235	17350
	GA	29632	17149
	Total	27934	17074
UAS Intruder_Low Traffic_150knots_Angle 7	ATP	22344	11746
	GA	26521	13031
	Total	24433	12399
UAS Intruder_Low Traffic_150knots_Angle 8	ATP	17863	8697
	GA	26373	17808
	Total	22118	14459
UAS Intruder_Low Traffic_250knots_Angle 1	ATP	13688	4570
	GA	19386	16228
	Total	16537	12090
UAS Intruder_Low Traffic_250knots_Angle 2	ATP	17919	8747
	GA	22673	13176
	Total	20296	11273
UAS Intruder_Low Traffic_250knots_Angle 3	ATP	22708	13906
	GA	31491	19208
	Total	27099	17103
UAS Intruder_Low Traffic_250knots_Angle 4	ATP	31932	24172
	GA	34891	20296
	Total	33411	22029
UAS Intruder_Low Traffic_250knots_Angle 5	ATP	36031	28417
	GA	39207	25515
	Total	37619	26642
UAS Intruder_Low Traffic_250knots_Angle 6	ATP	31749	22045
	GA	34541	19145
	Total	33145	20380
UAS Intruder_Low Traffic_250knots_Angle 7	ATP	23880	16240
	GA	29801	19925
	Total	26840	18149
UAS Intruder_Low Traffic_250knots_Angle 8	ATP	18943	9211
	GA	21253	12113
	Total	20098	10661
UAS Intruder_Medium Traffic_150knots_Angle 1	ATP	14062	4491

	GA	14562	4738
	Total	14312	4553
UAS Intruder_Medium Traffic_150knots_Angle 2	ATP	17715	8197
	GA	22798	13944
	Total	20256	11554
UAS Intruder_Medium Traffic_150knots_Angle 3	ATP	20671	9089
	GA	27622	15934
	Total	24146	13251
UAS Intruder_Medium Traffic_150knots_Angle 4	ATP	24389	14562
	GA	29804	18592
	Total	27097	16672
UAS Intruder_Medium Traffic_150knots_Angle 5	ATP	29598	18579
	GA	37846	20891
	Total	33722	19912
UAS Intruder_Medium Traffic_150knots_Angle 6	ATP	25288	17559
	GA	29859	16335
	Total	27573	16859
UAS Intruder_Medium Traffic_150knots_Angle 7	ATP	21703	12363
	GA	29678	14526
	Total	25690	13885
UAS Intruder_Medium Traffic_150knots_Angle 8	ATP	17632	9483
	GA	21858	11243
	Total	19745	10464
UAS Intruder_Medium Traffic_250knots_Angle 1	ATP	13549	4429
	GA	14115	4936
	Total	13832	4627
UAS Intruder_Medium Traffic_250knots_Angle 2	ATP	18426	8963
	GA	23382	13968
	Total	20904	11826
UAS Intruder_Medium Traffic_250knots_Angle 3	ATP	23164	14079
	GA	28853	17478
	Total	26009	15892
UAS Intruder_Medium Traffic_250knots_Angle 4	ATP	31322	22423
	GA	35065	19928
	Total	33194	20974
UAS Intruder_Medium Traffic_250knots_Angle 5	ATP	33690	25922
	GA	36187	20076
	Total	34939	22865
UAS Intruder_Medium Traffic_250knots_Angle 6	ATP	28722	17616
	GA	35363	21049
	Total	32042	19407
UAS Intruder_Medium Traffic_250knots_Angle 7	ATP	23344	15602
	GA	28955	19903
	Total	26150	17838
UAS Intruder_Medium Traffic_250knots_Angle 8	ATP	18152	9453
	GA	22265	11183
	Total	20208	10408

Table 2: *Five-way Mixed ANOVA Results for dOWN in feet (p* = significant)*

Effect	F	df	p
Angle	27.68	2, 56	< .001*
IntruderType	<1	1, 32	.692
OwnSpeed	9.75	1, 32	.004*
TrafficLevel	4.35	1, 32	.045*
Angle * Pilot_Type	<1	2, 56	.703
IntruderType * Angle	2.86	5, 175	.014*
IntruderType * OwnSpeed	1.08	1, 32	.306
IntruderType * Pilot_Type	<1	1, 32	.407
IntruderType * TrafficLevel	1.16	1, 32	.289
OwnSpeed * Angle	6.85	5, 175	< .001*
OwnSpeed * Pilot_Type	<1	1, 32	.989
TrafficLevel * Angle	<1	5, 146	.701
TrafficLevel * OwnSpeed	<1	1, 32	.509
TrafficLevel * Pilot_Type	<1	1, 32	.764
IntruderType * Angle * Pilot_Type	<1	5, 175	.489
IntruderType * OwnSpeed * Angle	<1	5, 176	.920
IntruderType * OwnSpeed * Pilot_Type	4.56	1, 32	.041*
IntruderType * TrafficLevel * Angle	<1	5, 171	.604
IntruderType * TrafficLevel * OwnSpeed	1.44	1, 32	.239
IntruderType * TrafficLevel * Pilot_Type	<1	1, 32	.967
OwnSpeed * Angle * Pilot_Type	<1	5, 175	.768
TrafficLevel * Angle * Pilot_Type	1.37	5, 146	.243
TrafficLevel * OwnSpeed * Angle	<1	6, 182	.731
TrafficLevel * OwnSpeed * Pilot_Type	1.83	1, 32	.186
IntruderType * OwnSpeed * Angle * Pilot_Type	2	5, 176	.165
IntruderType * TrafficLevel * Angle * Pilot_Type	1.57	5, 171	.927
IntruderType * TrafficLevel * OwnSpeed * Angle	<1	6, 183	.599
IntruderType * TrafficLevel * OwnSpeed * Pilot_Type	3.26	1, 32	.080
TrafficLevel * OwnSpeed * Angle * Pilot_Type	<1	6, 182	.696
IntruderType * TrafficLevel * OwnSpeed * Angle * Pilot_Type	1.27	6, 183	.277

Tests of Between-Subjects Effects	F	df	p
Pilot_Type	<1	1, 32	.337

Interaction Plots for WCB Distance from Ownship Metrics. Figure 16a is one of two figures that depicts the three way interaction present among intruder type, ownship speed, and pilot type measured by dOWN. It shows the interaction for ATPs. We can see how the effect of intruder and ownship speed interact, and when compared to Figure 16b below, how this interaction differs across pilot type. In Figure 16a, it evident that when ATPs traveled at the slower speed of 150 knots, they averaged a smaller WCB for UAS than manned intruders. However, when traveling at the higher speed of 250 knots, they indicated a significantly larger WCB for UAS over manned intruders.

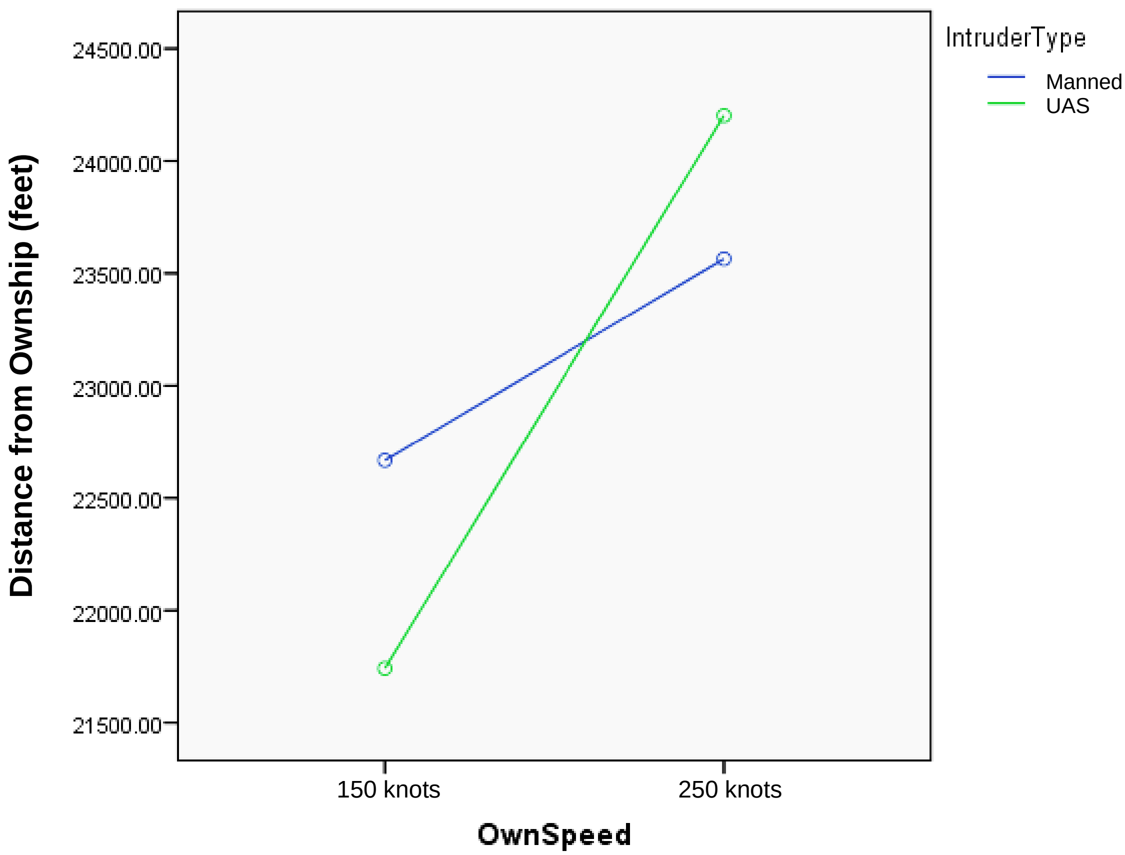

Figure 16a. Means of WCB by Ownship Speed between Intruder Types for ATPs

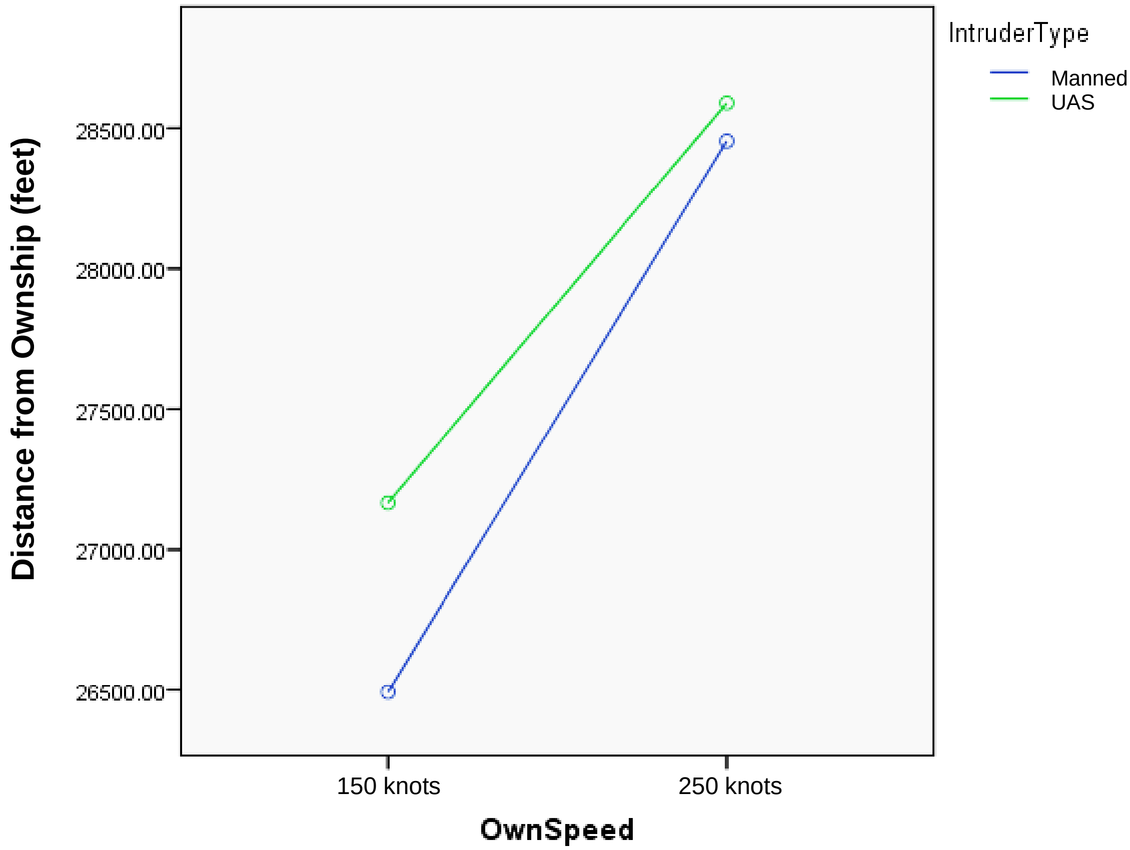

Figure 16b. Means of WCB by Ownship Speed between Intruder Types for GA Pilots

Figure 16b is the second of two depicting the three way interaction between intruder type, ownship speed, and pilot measured by dOWN, showing the effects of ownship speed and intruder type for GA pilots. We can see the effect of intruder and ownship speed for GA pilots differ from ATPs when compared to Figure 16a above. Here in Figure 16b it is evident that regardless of whether GA pilots were travelling at the slower or faster speeds, they averaged a larger WCB for UAS than manned intruders. This differs significantly from the WCB for ATPs, which changed between ownship speeds depending on intruder types.

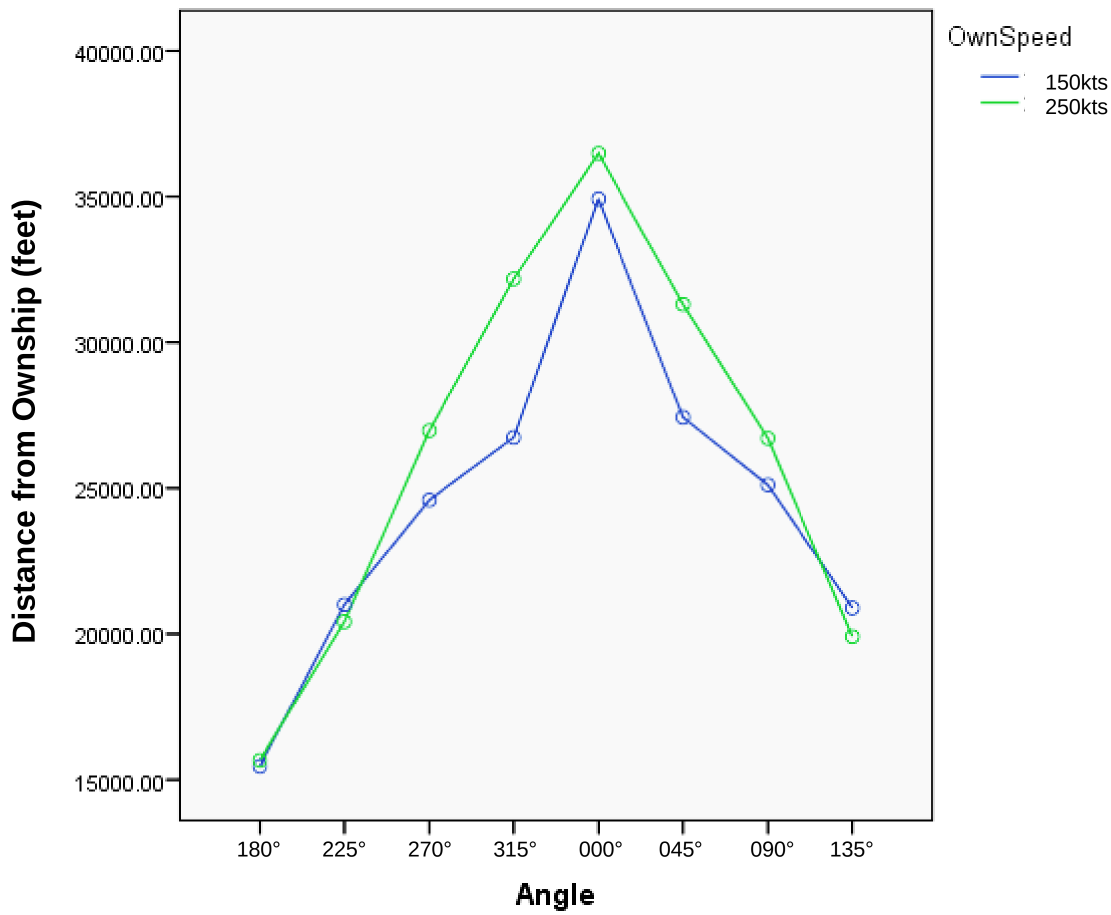

Figure 17. Means of WCB by Intruder Approach Angle for all Pilots

Figure 18 shows how the effect of ownship speed on the WCB depends on intruder approach angle when measured by dOWN for all pilots. So, aside from pilots averaging different WCB distances depending on intruder approach angle, these distances also differed significantly based on ownship speed. The largest differences in the WCB between ownship speeds are at the 315° and 045° angles (all relative to ownship bearing 000°). Oddly, we also see the WCB having smaller values at the higher speed of 250 knots from the 225° and 135° angles, an opposite trend from all other angles.

Time to Closest Point of Approach (tCPA). The second five-way ANOVA was performed on the tCPA measurement results, which were the times until ownship was projected to intersect flight paths (closest point of approach) with ownship from each of the eight intruder approach angles. This 8x2x2x2x2 ANOVA was used to analyze these data. Three interactions (see Figures 18-20) and two main effects were statistically significant. There was a significant four-way interaction among intruder type, traffic level, ownship speed, and intruder approach angle, $F(6,200) = 6.28$, $p = 0.008$. This shows that the effect of intruder type depends on traffic level and ownship speed, and this relationship differs across intruder approach angles. A significant three-way interaction was found among intruder type, traffic level, and ownship speed, $F(1, 32) = 4.16$, $p = 0.049$. This means that the effect of intruder type depends on traffic level, which differs across ownship speeds. A significant two-way interaction was observed between ownship speed and intruder approach angle, $F(5,170) = 6.85$, $p < 0.001$, indicating that the effect of ownship speed depends on intruder approach angle. Main effects were also found for intruder approach angle, $F(2, 83) = 370.02$, $p < 0.001$, and for ownship speed, $F(1, 32) = 8.57$, $p = 0.006$. Aside from these interactions, all other effects for the metric of tCPA in feet were not significant. For all tCPA means and standard deviations, as well as full tCPA interaction results, see Tables 3 and 4 below.

Table 3: Means and Standard Deviations for tCPA in seconds

Scenario	Pilot Type	Mean	Std. Deviation
Manned Intruder_Low Traffic_150knots_Angle 1	ATP	146.0471	23.29343
	GA	156.5706	44.36533
	Total	151.3088	35.29752
Manned Intruder_Low Traffic_150knots_Angle 2	ATP	58.0235	26.14459
	GA	78.3118	51.06435
	Total	68.1676	41.25178
Manned Intruder_Low Traffic_150knots_Angle 3	ATP	53.7176	26.39650
	GA	60.3824	33.51450
	Total	57.0500	29.89755
Manned Intruder_Low Traffic_150knots_Angle 4	ATP	42.0353	21.61458
	GA	52.6059	27.85883
	Total	47.3206	25.13155
Manned Intruder_Low Traffic_150knots_Angle 5	ATP	32.1176	29.78905
	GA	30.5235	30.60538
	Total	31.3206	29.74988
Manned Intruder_Low Traffic_150knots_Angle 6	ATP	48.0824	23.95666
	GA	51.5118	26.54058
	Total	49.7971	24.95642
Manned Intruder_Low Traffic_150knots_Angle 7	ATP	51.0882	27.84374
	GA	63.4000	33.46171
	Total	57.2441	30.94853
Manned Intruder_Low Traffic_150knots_Angle 8	ATP	61.9000	29.93881
	GA	81.8824	46.25137
	Total	71.8912	39.68144
Manned Intruder_Low Traffic_250knots_Angle 1	ATP	138.4059	30.41060
	GA	154.3353	45.25983
	Total	146.3706	38.81930
Manned Intruder_Low Traffic_250knots_Angle 2	ATP	62.5235	30.07546
	GA	71.2412	33.69967
	Total	66.8824	31.76103
Manned Intruder_Low Traffic_250knots_Angle 3	ATP	42.3706	24.52338
	GA	53.8000	33.03642
	Total	48.0853	29.23011
Manned Intruder_Low Traffic_250knots_Angle 4	ATP	42.3235	26.41904
	GA	42.2941	22.00033
	Total	42.3088	23.93912
Manned Intruder_Low Traffic_250knots_Angle 5	ATP	43.9882	32.00306
	GA	49.1706	28.64910
	Total	46.5794	30.02411

Manned Intruder_Low Traffic_250knots_Angle 6	ATP	40.7588	27.56726
	GA	43.7118	24.33408
	Total	42.2353	25.64781
Manned Intruder_Low Traffic_250knots_Angle 7	ATP	42.7529	25.00258
	GA	53.4059	32.76657
	Total	48.0794	29.20412
Manned Intruder_Low Traffic_250knots_Angle 8	ATP	54.5765	25.54996
	GA	70.1412	34.11006
	Total	62.3588	30.70878
Manned Intruder_Medium Traffic_150knots_Angle 1	ATP	139.0353	28.49995
	GA	155.7588	38.24644
	Total	147.3971	34.27953
Manned Intruder_Medium Traffic_150knots_Angle 2	ATP	60.2824	31.36322
	GA	76.9000	33.09732
	Total	68.5912	32.85071
Manned Intruder_Medium Traffic_150knots_Angle 3	ATP	49.4353	26.12247
	GA	58.7412	30.76028
	Total	54.0882	28.49421
Manned Intruder_Medium Traffic_150knots_Angle 4	ATP	44.8765	26.64208
	GA	47.2000	26.37314
	Total	46.0382	26.12985
Manned Intruder_Medium Traffic_150knots_Angle 5	ATP	31.2647	30.25213
	GA	25.8412	22.26845
	Total	28.5529	26.30084
Manned Intruder_Medium Traffic_150knots_Angle 6	ATP	45.3294	23.37880
	GA	50.5824	28.85453
	Total	47.9559	25.99591
Manned Intruder_Medium Traffic_150knots_Angle 7	ATP	48.0176	22.14182
	GA	59.8588	27.87062
	Total	53.9382	25.50361
Manned Intruder_Medium Traffic_150knots_Angle 8	ATP	58.8412	26.82881
	GA	73.5941	35.88371
	Total	66.2176	32.08362
Manned Intruder_Medium Traffic_250knots_Angle 1	ATP	145.9235	34.74058
	GA	157.1824	44.47027
	Total	151.5529	39.70714
Manned Intruder_Medium Traffic_250knots_Angle 2	ATP	56.5118	25.12491
	GA	70.5176	33.74925
	Total	63.5147	30.14699
Manned Intruder_Medium Traffic_250knots_Angle 3	ATP	44.2882	28.37263
	GA	54.8882	32.57315

	Total	49.5882	30.55612
Manned Intruder_Medium Traffic_250knots_Angle 4	ATP	39.1235	25.47956
	GA	46.7529	24.90535
	Total	42.9382	25.10977
Manned Intruder_Medium Traffic_250knots_Angle 5	ATP	42.2353	28.57241
	GA	49.7647	34.26228
	Total	46.0000	31.29840
Manned Intruder_Medium Traffic_250knots_Angle 6	ATP	39.0235	20.75595
	GA	42.1294	24.60236
	Total	40.5765	22.46840
Manned Intruder_Medium Traffic_250knots_Angle 7	ATP	40.8824	23.63769
	GA	55.6647	29.87541
	Total	48.2735	27.56694
Manned Intruder_Medium Traffic_250knots_Angle 8	ATP	55.2059	27.96083
	GA	72.0000	35.78049
	Total	63.6029	32.74798
UAS Intruder_Low Traffic_150knots_Angle 1	ATP	141.5882	23.56390
	GA	157.1412	35.96140
	Total	149.3647	30.96028
UAS Intruder_Low Traffic_150knots_Angle 2	ATP	62.4647	32.12291
	GA	82.3706	44.84892
	Total	72.4176	39.71909
UAS Intruder_Low Traffic_150knots_Angle 3	ATP	46.2824	24.46925
	GA	60.7118	31.82558
	Total	53.4971	28.89665
UAS Intruder_Low Traffic_150knots_Angle 4	ATP	46.7647	26.65774
	GA	50.6353	28.83301
	Total	48.7000	27.41321
UAS Intruder_Low Traffic_150knots_Angle 5	ATP	28.5412	28.41751
	GA	34.5059	33.89339
	Total	31.5235	30.94643
UAS Intruder_Low Traffic_150knots_Angle 6	ATP	47.5235	27.56174
	GA	52.9118	27.26951
	Total	50.2176	27.13557
UAS Intruder_Low Traffic_150knots_Angle 7	ATP	49.8529	23.83517
	GA	58.3588	26.47976
	Total	54.1059	25.18035
UAS Intruder_Low Traffic_150knots_Angle 8	ATP	60.0471	29.21288
	GA	84.9118	50.15820
	Total	72.4794	42.34167
UAS Intruder_Low Traffic_250knots_Angle 1	ATP	140.7294	32.54848

	GA	160.4588	48.23870
	Total	150.5941	41.73896
UAS Intruder_Low Traffic_250knots_Angle 2	ATP	58.9765	27.03739
	GA	71.7118	35.46921
	Total	65.3441	31.72035
UAS Intruder_Low Traffic_250knots_Angle 3	ATP	41.0353	23.14716
	GA	55.6706	32.04522
	Total	48.3529	28.51030
UAS Intruder_Low Traffic_250knots_Angle 4	ATP	43.7882	30.82410
	GA	47.5176	25.90367
	Total	45.6529	28.09951
UAS Intruder_Low Traffic_250knots_Angle 5	ATP	45.5588	33.48923
	GA	49.2529	30.08758
	Total	47.4059	31.40385
UAS Intruder_Low Traffic_250knots_Angle 6	ATP	43.6235	28.07858
	GA	47.1294	24.43133
	Total	45.3765	25.97739
UAS Intruder_Low Traffic_250knots_Angle 7	ATP	43.1000	27.09986
	GA	52.9765	33.30448
	Total	48.0382	30.31480
UAS Intruder_Low Traffic_250knots_Angle 8	ATP	61.6118	28.48850
	GA	67.7294	35.00791
	Total	64.6706	31.58082
UAS Intruder_Medium Traffic_150knots_Angle 1	ATP	147.2706	24.92155
	GA	155.0588	21.27087
	Total	151.1647	23.15437
UAS Intruder_Medium Traffic_150knots_Angle 2	ATP	59.0000	27.96672
	GA	74.7471	42.08414
	Total	66.8735	36.08036
UAS Intruder_Medium Traffic_150knots_Angle 3	ATP	46.6059	18.45367
	GA	60.7176	32.33911
	Total	53.6618	26.89734
UAS Intruder_Medium Traffic_150knots_Angle 4	ATP	43.8059	23.09403
	GA	52.4235	29.55490
	Total	48.1147	26.48067
UAS Intruder_Medium Traffic_150knots_Angle 5	ATP	24.3000	19.75373
	GA	32.0353	26.02698
	Total	28.1676	23.08772
UAS Intruder_Medium Traffic_150knots_Angle 6	ATP	46.0353	27.86878
	GA	53.2588	25.96681
	Total	49.6471	26.77551

UAS Intruder_Medium Traffic_150knots_Angle 7	ATP	48.5765	25.09000
	GA	64.7706	29.50095
	Total	56.6735	28.19099
UAS Intruder_Medium Traffic_150knots_Angle 8	ATP	59.1235	32.09799
	GA	72.6529	35.30462
	Total	65.8882	33.92641
UAS Intruder_Medium Traffic_250knots_Angle 1	ATP	141.2412	34.27423
	GA	146.7176	30.10586
	Total	143.9794	31.88630
UAS Intruder_Medium Traffic_250knots_Angle 2	ATP	60.5412	27.69574
	GA	73.5588	36.82813
	Total	67.0500	32.75910
UAS Intruder_Medium Traffic_250knots_Angle 3	ATP	41.8000	23.45365
	GA	51.2706	29.15012
	Total	46.5353	26.49142
UAS Intruder_Medium Traffic_250knots_Angle 4	ATP	43.0000	28.56851
	GA	47.7412	25.41739
	Total	45.3706	26.73457
UAS Intruder_Medium Traffic_250knots_Angle 5	ATP	42.7824	30.54004
	GA	45.6706	23.64191
	Total	44.2265	26.93260
UAS Intruder_Medium Traffic_250knots_Angle 6	ATP	39.7765	22.38215
	GA	48.2294	26.85370
	Total	44.0029	24.71697
UAS Intruder_Medium Traffic_250knots_Angle 7	ATP	42.2059	26.01561
	GA	51.5588	33.25643
	Total	46.8824	29.78122
UAS Intruder_Medium Traffic_250knots_Angle 8	ATP	59.1647	29.24060
	GA	71.0235	32.70456
	Total	65.0941	31.13459

Effect	F	df	p
Angle	370.02	3, 83	< .001*
IntruderType	<1	1, 32	.460
OwnSpeed	8.57	1, 32	.006*
TrafficLevel	3.87	1, 32	.058
Angle * Pilot_Type	1.70	3, 83	.179
IntruderType * Angle	1.36	4, 139	.250
IntruderType * OwnSpeed	<1	1, 32	.782
IntruderType * Pilot_Type	<1	1, 32	.644
IntruderType * TrafficLevel	<1	1, 32	.579
OwnSpeed * Angle	19.85	5, 171	< .001*
OwnSpeed * Pilot_Type	<1	1, 32	.339
TrafficLevel * Angle	<1	4, 118	.773
TrafficLevel * OwnSpeed	3.05	1, 32	.090
TrafficLevel * Pilot_Type	<1	1, 32	.787
IntruderType * Angle * Pilot_Type	1.02	4, 139	.405
IntruderType * OwnSpeed * Angle	<1	6, 183	.890
IntruderType * OwnSpeed * Pilot_Type	3.35	1, 32	.076
IntruderType * TrafficLevel * Angle	<1	5, 163	.875
IntruderType * TrafficLevel * OwnSpeed	4.19	1, 32	.049*
IntruderType * TrafficLevel * Pilot_Type	<1	1, 32	.356
OwnSpeed * Angle * Pilot_Type	<1	5, 171	.543
TrafficLevel * Angle * Pilot_Type	<1	4, 118	.455
TrafficLevel * OwnSpeed * Angle	<1	6, 202	.572
TrafficLevel * OwnSpeed * Pilot_Type	<1	1, 32	.378
IntruderType * OwnSpeed * Angle * Pilot_Type	1.24	6, 183	.288
IntruderType * TrafficLevel * Angle * Pilot_Type	<1	5, 163	.496
IntruderType * TrafficLevel * OwnSpeed * Angle	2.97	6, 201	.008*
IntruderType * TrafficLevel * OwnSpeed * Pilot_Type	1.29	1, 32	.265
TrafficLevel * OwnSpeed * Angle * Pilot_Type	1.62	6, 202	.140
IntruderType * TrafficLevel * OwnSpeed * Angle * Pilot_Type	1.16	6, 201	.328

Tests of Between-Subjects Effects	F	df	p
Pilot_Type	1.20	1, 32	.282

Table 4: *Effects of all interactions for tCPA in seconds (p* = significant)*

Interaction Plots for WCB Time to Closest Point of Approach Metrics. Figures 18a through 18d collectively depict the four-way interaction observed among intruder type, traffic level, ownship speed, and intruder approach angle. Figure 18a represents a portion of the four-way interaction showing average time to closest point of approach by intruder approach angle across ownship speeds for ATPs interacting with manned intruders. Figure 18b shows another portion of the same interaction, but for GA pilots interacting with manned intruders. In both of these plots we can see ATP and GA pilots averaging a significantly larger tCPA when traveling at the lower speed of 150 knots for all intruder approach angles, except for 000° (the head-on angle). In the head-on angle we can see a significantly lower tCPA value compared to all other angles. This head-on value difference is even more drastic in the GA pilot plot in Figure 18b when compared to the ATP plot in Figure 18a. Additionally, we can see that ownship speed had less of an effect on tCPA for GA pilots than for ATPs in this particular interaction. While Figures 19 and 20 only represent half of the four-way interaction (all interactions with manned intruders only), Figures 19 and 20 below them represent the remaining portions of the interaction.

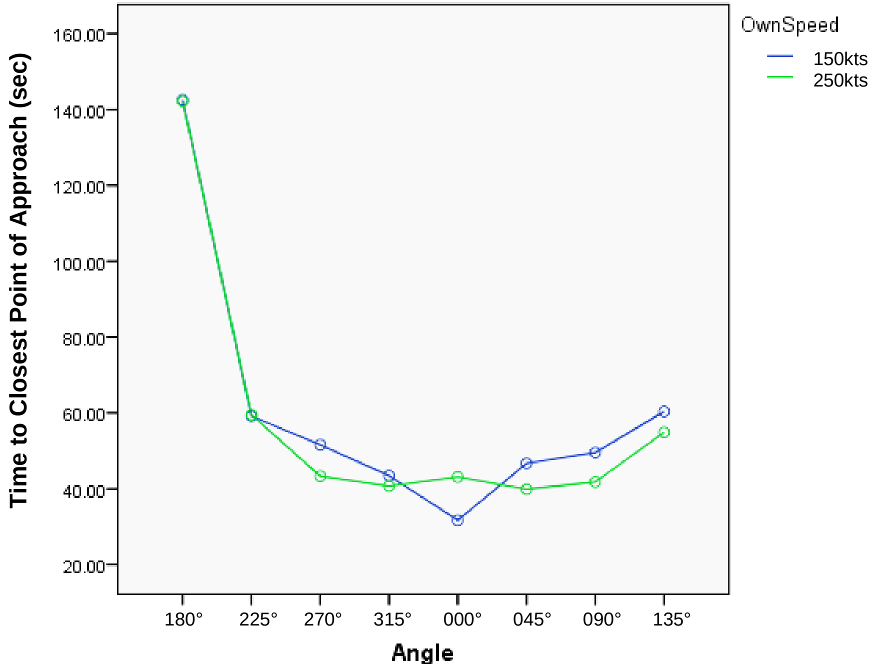

Figure 18a. Mean Time to CPA by Intruder Approach Angle between Ownship Speeds for ATPs interacting with Manned Intruders

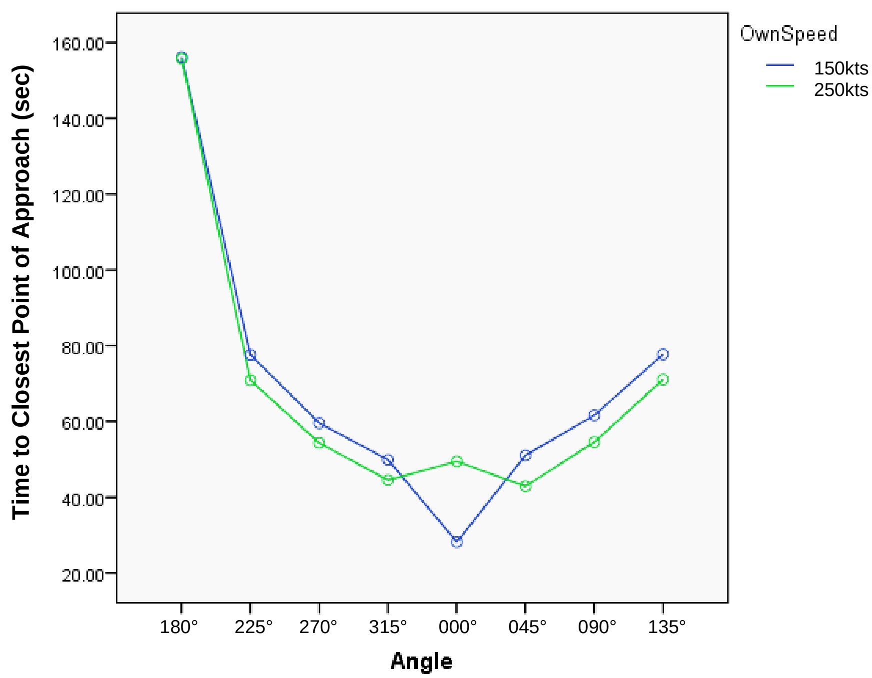

Figure 18b. Mean Time to CPA by Intruder Approach Angle between Ownship Speeds for GA Pilots interacting with Manned Intruders

Figures 18c and 18d depict the second half of the four-way interaction observed among intruder type, traffic level, ownship speed, and intruder approach angle. Figure 18c represents the portion of the four-way interaction showing average time to closest point of approach by intruder approach angle across ownship speeds for ATPs interacting with UAS intruders. Figure 18d shows another portion of the same interaction, but for GA pilots interacting with UAS intruders. Just as seen in the first two plots for this interaction in Figures 19 and 20, both of the plots in Figures 21 and 22 show ATP and GA pilots averaging a significantly larger tCPA when traveling at the lower speed of 150 knots for all intruder approach angles, except for 000° (the head-on angle). In the head-on angle we can see a significantly lower tCPA value compared to all other angles. However, this time the head-on value difference is more drastic in the ATPs' (as opposed to with GA pilots in Figures 19 and 20) plot in Figure 18c when compared to the GA pilots plot in Figure 18d. Additionally, we can see that ownship speed had less of an effect on tCPA for GA pilots than for ATPs in this particular interaction. The last thing to notice in this four-way interaction is that we can see that the effect of ownship speed had greater differences in tCPA values with ATPs interacting with manned intruders (Figure 18b) when compared to ATPs interacting with UAS intruders (Figure 18d), except of course for the head-on condition where the opposite is true.

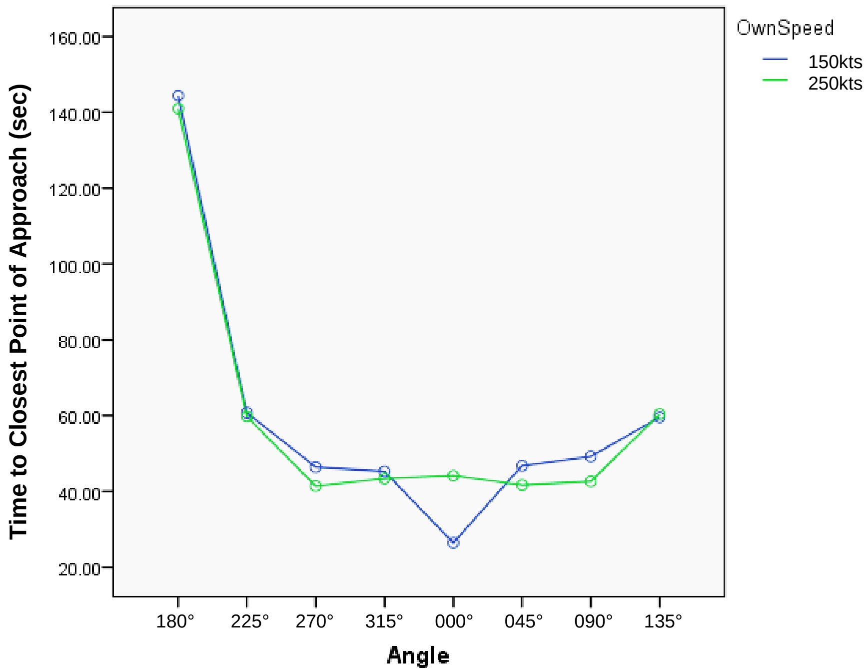

Figure 18c. Mean Time to CPA by Intruder Approach Angle between Ownship Speeds for ATPs interacting with UAS Intruders

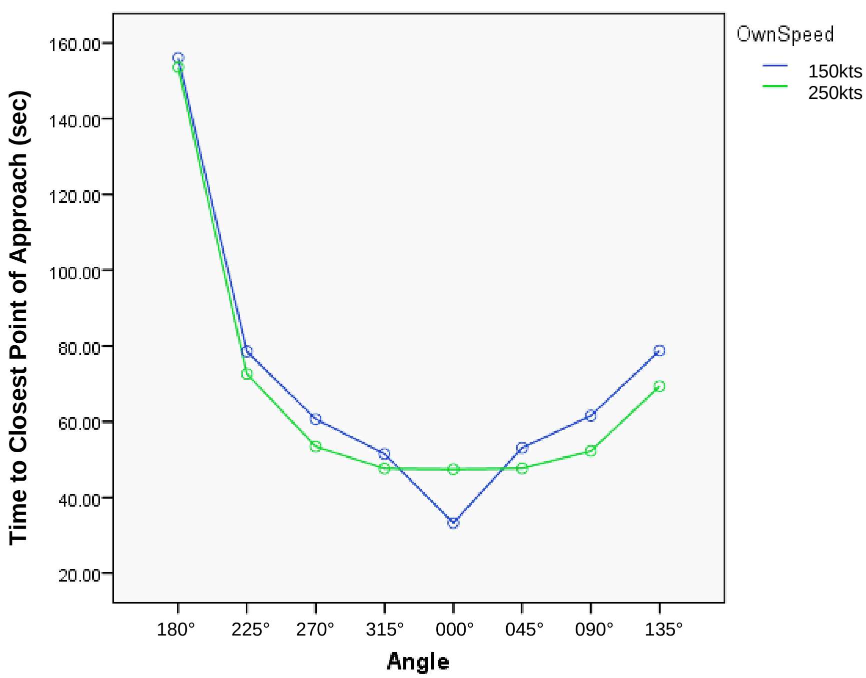

Figure 18d. Mean Time to CPA by Intruder Approach Angle between Ownship Speeds for GA Pilots interacting with UAS Intruders

Figures 19a and 19b below depict the three way interaction among intruder types, traffic levels, and ownship speeds. Figure 19a shows average time to CPA for intruder types based on ownship speed in low traffic level. This plot indicates that while interacting with the low background traffic level, all pilots had a slightly larger value of the WCB for the manned over UAS intruders at the lower ownship speed of 150 knots, while having a significantly smaller WCB for manned compared to UAS intruders at the higher ownship speed of 250 knots. Conversely, we can see in Figure 19b that when interacting with the medium background traffic level all pilots showed a significantly larger WCB for UAS compared to manned intruders at the lower ownship speed, and a slightly smaller WCB for UAS over manned intruders at the higher ownship speed.

The final plot in Figure 20 below depicts the significant two-way interaction between ownship speed and intruder approach angle when measured by time to CPA. Similar to the findings mentioned previously for the dOWN measurements, the plot shows larger values for the slower ownship speed of 150 knots versus the faster speed of 250 knots due to the difference in closure rate given the intruder angle. Again we see an exception for the 000° or head-on angle where the value trend reverses from all other angle-ownship speed differences. In the head-on angle we see a significantly lower tCPA WCB value for the 150 knot ownship speed as opposed to other angles and ownship speeds.

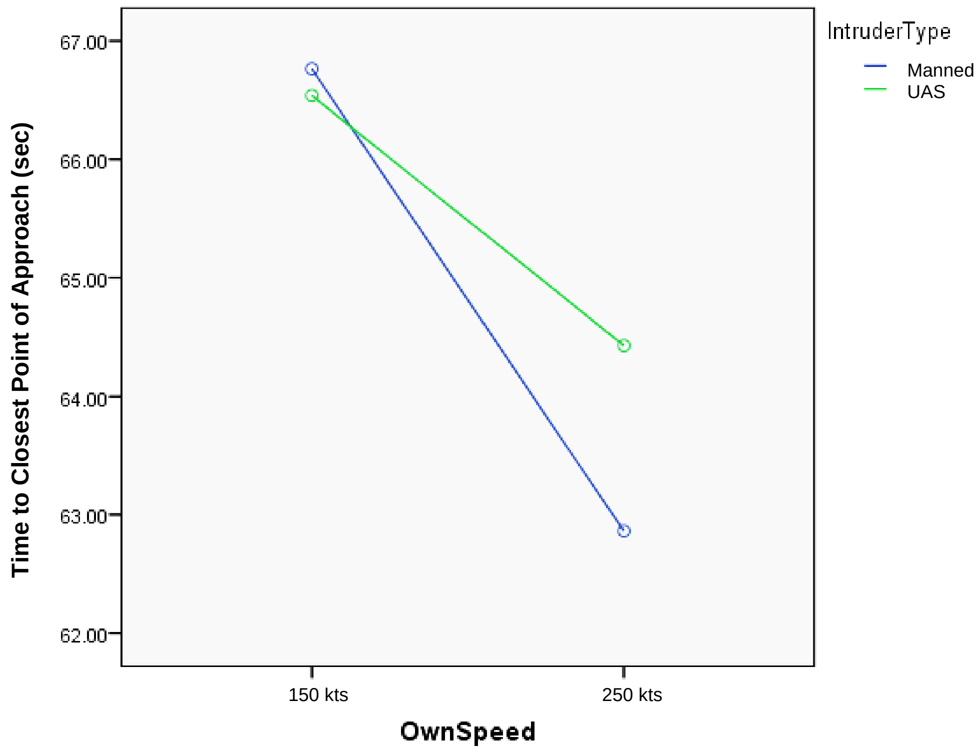

Figure 19a. Time to CPA for Intruder Types based on Ownship Speed in Low

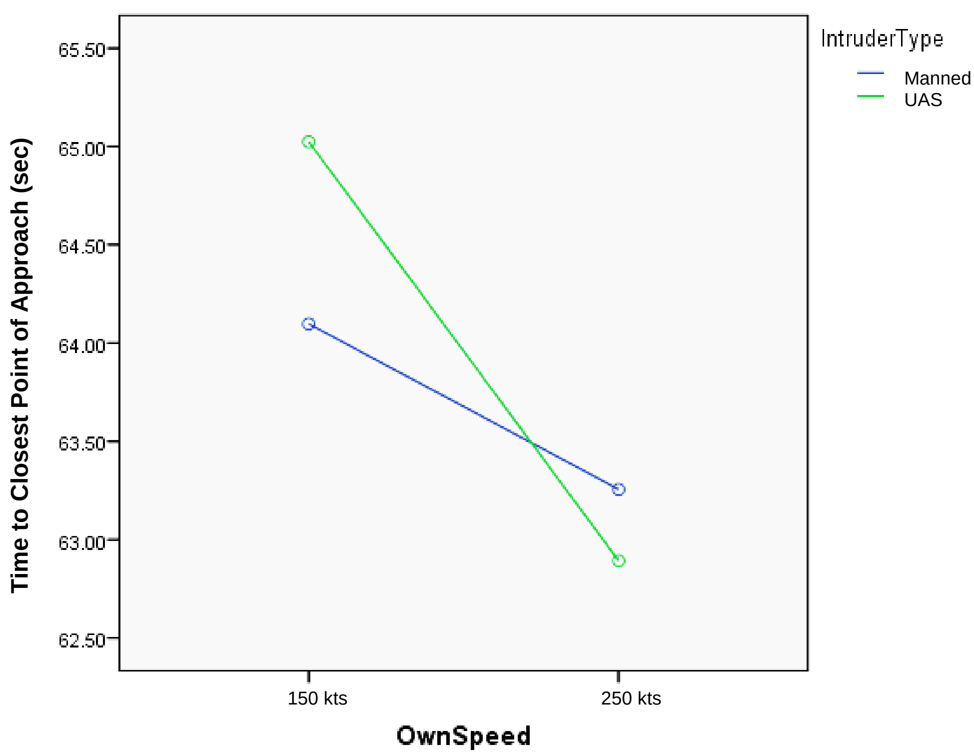

Figure 19b. Time to CPA for Intruder Types based on Ownship Speed in Medium

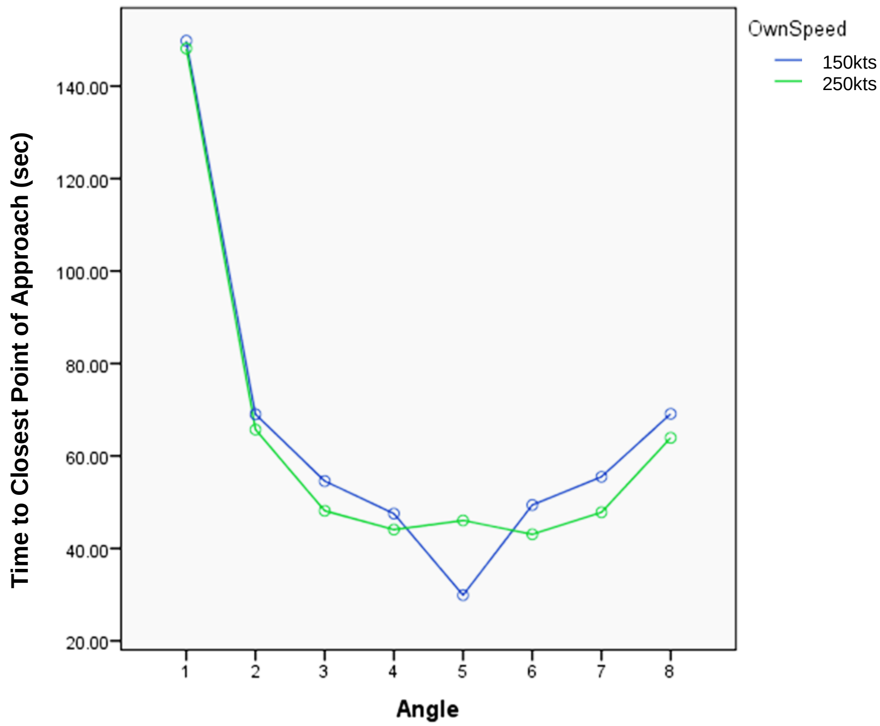

Figure 20. Time to CPA by intruder Approach Angle between Ownship Speeds

Subjective Metrics Results

Pilot post-simulation subjective questionnaires are listed by question type: WCB perception, CDTI/CSD technology preferences, manned vs. unmanned intruder types, UAS specific questions, and other pilot type opinions. The tables below show responses given by pilots, broken down into percentages of overall responses and also corresponding responses by pilot type. If any instance of answer percentages does not sum to 100%, it was due to some questions being omitted or misinterpreted by participants.

Table 5: Subjective Questions about WCB Perception

Question	Overall Response	Response by Pilot Type	
What unit of measurement do you first think of when measuring the well clear boundary (WCB) from ownship position?	Distance = %32.4	ATP = %17.6	GA = %47.1
	Time = %35.3	ATP = %41.2	GA = %26.4
	Both = %32.4	ATP = %41.2	GA = %23.5
What affects your opinion of the WCB the most?	Closure Rate = %47.1	ATP = %52.9	GA = %41.2
	Intruder Angle = %11.8	ATP = %5.9	GA = %17.6
	Maneuverability = %17.6	ATP = %17.6	GA = %17.6
How do you believe WCB to be different from other similarly defined terms?	Varies Subjectively = %76.5	ATP = %76.5	GA = %76.5
	Has lower minimums = %5.9	ATP = %5.9	GA = %5.9
	VFR Conditions only = %8.9	ATP = %11.8	GA = %5.9
Do you feel comfortable with the current definition of Well Clear?	Yes = %55.9	ATP = %58.8	GA = %52.9
	No = %32.4	ATP = %35.3	GA = %29.4
	Depends (equipment/WX) = %11.8	ATP = %5.9	GA = %17.6
All scenarios measured WCB in 2D. What should the vertical WCB be?	1000' = %70.6	ATP = %23.5	GA = %47.1
	>1000 = %8.9	ATP = %23.5	GA = %29.4
	Too complicated = %26.5	ATP = %5.9	GA = %11.8
Rating Scale Questions (1 Strongly Disagree – 5 Strongly Agree)			
Did you feel speed of ownship changed your perceived dimensions of the WCB?	4	ATP = 4.2	GA = 3.9
Do you believe traffic density in your surroundings affected your perception of WCB?	3	ATP = 2.9	GA = 2.5

In Table 5, it can be collectively observed that responses for how participants *primarily* perceived the WCB indicated that they consider it to be a factor of distance, time, or both. Yet, more than double the percentage of GA pilots thought of the WCB as a measurement of distance. Almost double the percentage of ATPs primarily thought of the WCB in terms of time, or combination of time and distance than GA pilots did. When asked what affected the WCB opinion the most, all pilot types mostly agreed closure rate was the biggest factor over intruder angle or aircraft maneuverability. All pilots believed the WCB to be different from other similar terms mainly because it varies personally while other definitions have set parameters. Over half of overall pilot responses showed they were comfortable with the current definition of Well Clear. When asked what the vertical component of WCB should be most pilots thought it should be 1000 feet vertical separation. ATPs were split in their want between 1000 feet and greater than 1000 feet while most GA pilots agreed upon 1000 feet. Both pilot types strongly agreed that ownship speed affected WCB dimensions. Pilots moderately agreed that background traffic density affected the WCB.

Table 6: Subjective Questions about Manned vs. Unmanned Intruders

Question	Overall Response	Response by Pilot Type	
Do you believe UAS should abide to the exact same WCB as manned vehicles if you were flying a manned aircraft?	Yes = %50.0 No = %47.1 Unsure = %2.9	ATP = %41.2 ATP = %52.9 ATP = %5.9	GA = %58.9 GA = %41.2 GA = %0.0
Did you experience any difference in arousal (stress) with Manned vs UAS intruders?	Yes = %26.5 No = %73.5	ATP = %29.4 ATP = %70.6	GA = %23.5 GA = %76.5
What direction did the intruder feel most threatening from?	Head-on = %58.8 Overtake = %14.7 Right/Left = %26.5	ATP = %41.2 ATP = %17.6 ATP = %41.2	GA = %76.5 GA = %11.8 GA = %11.8
What was your perceived level of safety during interaction with **Manned** intruding aircraft?	Very Safe = %23.5 Safe = %70.9 Less Safe (than UAS) = %2.9	ATP = %29.4 ATP = %64.7 ATP = %0	GA = %17.6 GA = %64.7 GA = %5.9
What was your perceived level of safety during interaction with **UAS** intruding aircraft?	Very Safe = %17.6 Safe = %52.9 Less Safe (than Man) = %26.5	ATP = %17.6 ATP = %41.2 ATP = %35.3	GA = %17.6 GA = %64.7 GA = %17.6
Rating Scale Questions (1 Very Low Trust – 5 Very High Trust)			
Please rate the overall trust level you felt towards the **Manned** intruding aircraft	3	ATP = 2.9	GA = 3.9
Please rate the overall trust level you felt towards the **UAS** intruding aircraft	3	ATP = 2.4	GA = 3.2

In Table 6, when asked if UAS should abide by the same WCB as manned aircraft, responses were almost 50/50 split. Nearly half the pilots answered yes, while barely below half said no. GA pilots answered yes more than ATPs. When asked about arousal differences, most of both pilot types answered no, while almost a third experienced more stress with UAS intruders. Both pilot types felt that the most threatening intruder angle was from head-on approaches. Yet, for ATPs this was closely followed by right/left directions, and trailed by overtake (rear) directions. When asked about perceived safety levels both pilot types felt much safer with manned intruders over UAS. Yet, GA pilots showed an even split in opinion. When asked to rate perceived trust levels between intruder types, both pilot types trusted manned and UAS evenly. GA pilots showed higher trust ratings. When dissected by pilot type the responses showed slightly higher ratings for manned trust than UAS intruders overall.

Table 7: Subjective Questions UAS Specific

Question	Overall Response	Response by Pilot Type	
Do you feel confident that the UAS can abide by current WCB definition autonomously?	Yes = %35.3 No = %55.9 Depends on equipment = %11.8	ATP = %29.4 ATP = %58.8 ATP = %11.8	GA = %41.2 GA = %52.9 GA = %11.8
Would your WCB change if there were 2 or more UASs involved instead of just one?	Yes = %35.3 No = %55.9 Maybe = %8.8	ATP = %58.8 ATP = %29.4 ATP = %11.8	GA = %11.8 GA = %82.4 GA = %5.9
How do you feel in terms of the safe integration of UAS's into our national airspace system?	Safe if proven = %34.7 Unsafe/complicates things = %23.5 Mixed feelings = %11.8	ATP = %64.7 ATP = %29.4 ATP = %23.5	GA = %64.7 GA = %17.6 GA = %17.6

In Table 7, we can see when asked if UAS could autonomously abide the current WCB definition, over half of all pilots and pilot types said no with a higher yes answer percentage for GA pilots over ATPs. When asked if their WCB would change if two or more UASs were involved, half of all pilots said no. When broken down by pilot type most GA pilots said no, while over half of ATPs said yes. When asked how they felt about UAS integration, most pilots answered safe if proven. A lower percentage felt that it was unsafe, with more ATPs than GA pilots offering the response of unsafe.

Table 8: Subjective Questions about CDTI/CSD Technology

Question	Overall Response	Response by Pilot Type	
What system (if any) do you primarily use as a CDTI?	TCAS = %41.2 Other = %11.8 None = %47.1	ATP = %76.5 ATP = %17.6 ATP = %5.9	GA = %5.9 GA = %5.9 GA = %88.2
Do you feel your current CDTI display is adequate enough to allow safe perception of WCB?	Yes = %26.5 No = %26.5 N/A (Mostly GA) = %47.1	ATP = %52.9 ATP = %41.2 ATP = %5.9	GA = %0.0 GA = %11.8 GA = %88.2
Do you envision yourself relying more on a CDTI to maintain the WCB, or out-the-window view?	CDTI = %58.8 Out-the-Window = %38.2	ATP = %47.1 ATP = %52.9	GA = %70.6 GA = %23.5
Rating Scale Question (1 Strongly Disagree – 5 Strongly Agree)			
Did the CSD have positive impact on WCB perception compared to your CDTI?	4	ATP = 3.9	GA = 3.9

As can be seen in Table 8, although most GA pilots did not have any experience with a CDTI while most ATPs did. For ATPs, when asked if their current display was adequate for WCB perception, more than half said yes with just over 40% said no. Pilots were also asked if they envisioned themselves primarily utilizing a CDTI or out-the-window view to maintain WCB, and most answered they would use a CDTI. All pilots strongly agreed that the CSD was better for WCB perception compared to their current CDTI or other detection method.

Table 9: Subjective Question about WCB Opinion of other Pilot Type

Question	Response
ATP Pilots Only – Do you believe pilots with **less** experience than you would have a different opinion of the WCB?	Yes = %94.1 No = %5.8 Maybe = %0.0
GA Pilots Only – Do you believe pilots with **more** experience than you would have a different opinion of the WCB?	Yes = %41.2 No = %29.4 Maybe = %29.4

Table 9 shows that all ATPs except one agreed yes to the question, while GA pilots often responded yes with an equal split response between no and maybe.

Subjective WCB Map Drawings

After all subjective and objective data collection took place, pilots were asked to draw their version of a WCB map in terms of distance surrounding ownship. The only instruction given was to draw it as they saw fit on a blank map that only had ownship in the center as well as two range rings for scale, and to indicate a range on one of the range rings to help gauge the drawing's WCB size. They were asked to draw two maps, one for manned, and one for unmanned intruders. This hand-drawn map was done to visualize pilot's top down view of the WCB, as well as further depict any differences that intruder type had on the WCB. Drawings were first grouped by shape type, then by WCB size, and tallied accordingly. Full depictions of every map can be seen in Appendix Section C. Maps were categorized initially by three general shape categories: greater distance in front with less in rear, circular, and other. An example of each can be seen below in Figures 21, 22, and 23.

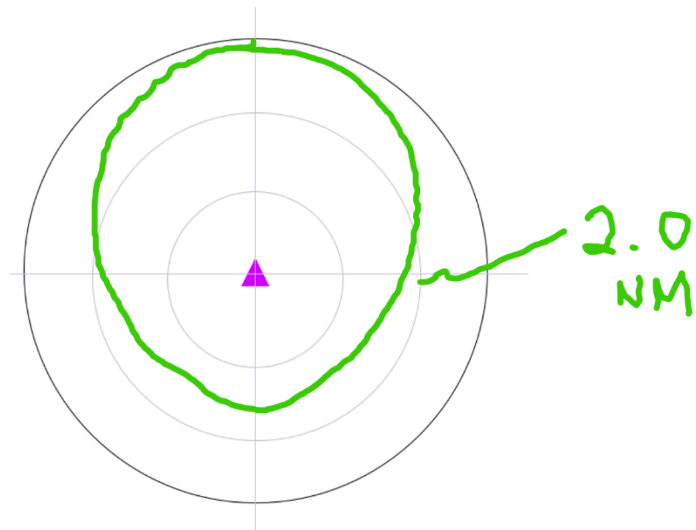

Figure 21. WCB drawing example – greater distance in front with less in rear

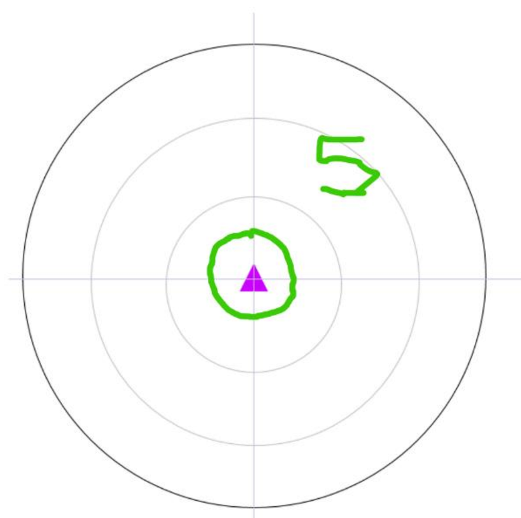

Figure 22. WCB drawing example – circular

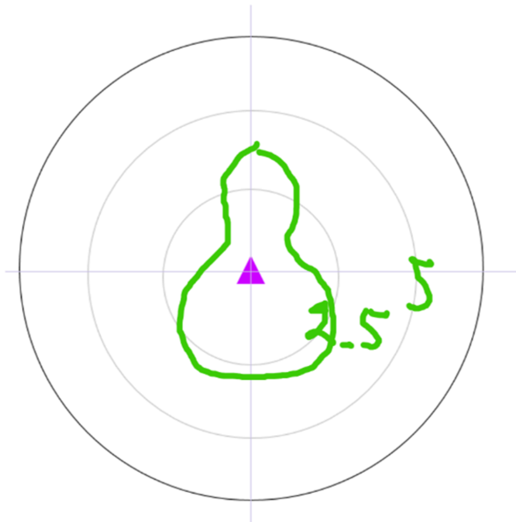

Figure 23. WCB drawing example – other

Table 10: WCB Drawing Shape Summary

WCB Drawing general Shape	Overall	ATPs	GA Pilots
Greater distance in front, less in rear	%50.0	%47.1	%52.9
Circular	%41.2	%47.1	%35.3
Other	%8.8	%5.9	%11.8

As we can see in Table 10, overall half of both pilot types depicted WCB maps with greater distance in front and less in the rear. This percentage was slightly higher with GA pilots than ATPs. Circular WCB maps closely followed for both pilot types, matching the percentage for greater in front less in rear for ATPs, and consisting of about 1/3 of the opinion for GA pilots. WCB maps classified as “other” made up a very small percentage, and serve to illustrate how differently humans can think and vary their opinion even when given the same information.

Discussion

The purpose of this thesis research was to determine how different pilot types perceived the subjective concept of the Well Clear Boundary, and to observe if that boundary changed when dealing with manned versus unmanned aircraft. The present study used an 8 x 2 x 2 x 2 x 2 mixed design that included four repeated-measures factors and a single between-subjects factor. Independent manipulations consisted of intruder approach angle (8 angles every 45° surrounding ownship), intruder type (manned vs. UAS), ownship speed (150 knots vs. 250 knots), traffic level (4 background aircraft vs. 8 background aircraft), and the between-subjects variable of pilot type (Commercial/ATP vs. GA pilots). The effects of these variables were assessed through objective measures of distance from ownship and time to closest point of approach, as well as subjectively through custom questionnaires to gauge overall perception of the WCB.

The Well Clear Boundary

To quantifiably determine pilot perception of the WCB, experimental data were recorded in a part-task CDTI simulator. WCB was determined by simulating multiple intruding aircraft set on a collision course with participants' ownship as indicated on the display. Pilots indicated the WCB by clicking a mouse button when an intruder was felt to no longer be well clear from them, with each trial representing a different combination of independent variables present during encounters from 8 angles surrounding ownship. Recording the position, trajectory, and speeds of ownship and intruders allowed the WCB to be calculated in two ways.

The dOWN Metric. The first method of calculating the WCB was by distance from ownship (dOWN), in other words an own-ship-centric metric with ownship located in the middle of a surrounding boundary measured in feet from ownship to intruding aircraft crossing the WCB. Overall, when measured by dOWN, the WCB followed the findings and propositions of suggested WCB definitions, with a much larger distance value in front of ownship compared to the rear. In this experiment, the WCB was found to average 35,701 feet directly in front of ownship, while it was 15,559 feet directly behind the aircraft. The two angles 45° to the left and right of ownship nose averaged 29,362 and 29,454 feet respectively, while the two angles 45° to the left and right of the rear of ownship measured 20,399 and 20,711 respectively. The 90° angles right and left of ownship measuring 25,909 and 25,781 respectively. We can observe an obvious pattern of greater values in the front with lower values in the rear of ownship are evident when measured in dOWN. Of course, this is due to difference in closure rates from these different angles. However, notice the extreme lower variability (as in the difference from angle to angle in dOWN values) in distance values for the 90° sides and all rear angles as opposed to the high degree of variability of the 3 angles in front of the aircraft. This could be key in fully understanding pilot perception of the WCB in terms of direction and distance.

The WCB measured in dOWN also displayed differences when collapsed across different independent variables. When WCB measurements were compared by pilot type, GA pilots averaged a larger value for every angle than ATPs did. This could be due to the fact most GA piloting experiences involve flying smaller aircraft at lower altitudes and slower airspeeds than ATPs. Therefore, they are not only more accustomed to having more time to react, but they are also used to an environment of looser ATC control over their aircraft since they travel in class E (uncontrolled airspace) much more frequently than ATPs in scheduled airlines. Additionally, most GA pilots did not have experience with cockpit traffic display technology of any kind and consequently rely on out-the window visual monitoring to avoid aircraft. Since this experiment only had a CDTI view (no out-the-window), perhaps GA pilots were more conservative in their WCB interpretations due to lack of CDTI experience.

The most significant differences in WCB dOWN appeared between the alternate ownship speeds tested. Ownship speed was present in all dOWN significant interactions, clearly having a strong effect on the WCB. Faster speeds yielded a larger WCB value for every approach angle. At 250 knots ownship speed all pilots pushed out the WCB in every angle, but especially at the front 45° left and right of their nose. These angles (315° and 45° relative to ownship) showed differences of nearly 4000' as opposed to approximately 1000' for other angles. This indicates the importance of the forward 45° angles from ownship nose in pilots' WCB perception. This may be not only be because intruders approaching from the front have a high closure rate, but because they likely would have a hard time judging an aircraft's distance and direction from these angles. For example, if an intruding aircraft is turning at these angles, the direction that it starts turning in may be difficult to interpret due to relative motion between ownship and intruder. If the intruder turned to the right, while ownship moved forward, the intruder may turn at a rate that appears to have no relative motion if their turn is gradual enough. This can add confusion since intruders with no relative motion in the sky are of the most danger since this indicates they can be heading straight for ownship. However the intruder turn could continue to the right and change visual relative motion cues often during its maneuver, creating the potential to mislead.

Another interesting dOWN WCB finding had to do with differences between intruder types. Although significant differences in intruder type depended on ownship speed which differed across pilot type, the manned intruders had slightly larger values for the head-on and rear approach angles, as well as the 90° and 270° angles than UAS intruders. Yet, the manned intruders had slightly smaller values for the 315°, 45°, 225°, and 135° angles than UAS. While the differences may not be great between intruders for most angles (approx. 500-1000'), the biggest difference was in the 315° and 45° angles which varied almost 2000' each. The patterns of these results are a bit scattered, but also show the importance of the pilots' perception of the forward 45° left and right of their nose. This difference is perhaps due to a mix in opinions of trust about manned versus unmanned intruders, which the subjective metrics also revealed.

The main effects for the dOWN metric were found to be most significant with intruder approach angle. This is not surprising considering how much the WCB varies in value depending on direction surrounding ownship. The main effect of ownship speed closely followed, and this trend is evident in Figures 10 and 11 even before statistical analysis was applied, showing how deeply ownship speed impacts the dOWN WCB from all angles, with greater speeds increasing WCB size. The background traffic level also was a dOWN main effect, not as significantly as the others, but still an important finding. This IV had significance of just under p=.05, visible in Figures 14 and 15 showing slightly smaller dOWN WCB values in the medium background traffic than the low traffic level scenarios.

The tCPA Metric. The second method of calculating the WCB was by time to closest point of approach (tCPA), which, unlike dOWN, is not an ownship centric metric. It involved measuring the time until the intruder aircraft reaches its closest point of approach (or in the case of this research, collide) with ownship. In this experiment, the tCPA WCB was found to average 38 seconds directly in front of ownship, while it was 149 seconds directly behind the aircraft. The two angles 45° to the left and right of ownship nose both averaged 46 seconds, while the two angles 45° to the left and right of the rear of ownship both averaged 67 seconds. The 90° angles right and left of ownship measured 52 and 51 seconds respectively. The differences found in the tCPA metrics when collapsed across independent variables correlate precisely with the dOWN metric findings, but with one fundamental difference. All tCPA results essentially assumed a mirrored shape of the dOWN WCB shape across the horizontal axis. In other words, greater tCPA values were found behind the ownship with much smaller values located towards the front of ownship. Again, this is due to differences in closure rates. Since intruding aircraft approaching from the front of ownship had such high closure rates, their time until collision was very short. Conversely, the intruders approaching the rear of ownship had an extremely slow closure rate with extremely high time values until collision.

One interaction unique to the tCPA metric is the four-way interaction observed among intruder type, traffic level, ownship speed, and intruder approach angle. When interacting with manned intruders, this interaction shoes both pilot types averaging a significantly larger tCPA when traveling at the lower speed of 150 knots for all intruder approach angles, except the head-on angle. In the head-on angle we can see a lower tCPA value compared to all other angles. This head-on value difference is even more drastic in the GA pilot data than ATPs. We can also see that ownship speed had less of an effect on tCPA for GA pilots in this interaction. Interestingly, when interacting with UAS intruders, this interaction shows the head-on value difference being more drastic in the ATPs' when compared to the GA pilots. Additionally, we can see that ownship speed had less of an effect on tCPA for GA pilots than for ATPs with UAS intruders. Aside from the differences in intruder type tCPA values across pilot types in this four-way interaction, we can see that the effect of ownship speed had greater differences in tCPA values with ATPs with manned intruders compared to ATPs with UAS intruders. This is true for all angles except for the head-on condition where the opposite is true.

The results regarding this head-on angle obscurity may be due to the fact that when traveling at 150 knots, there is much more time to react before a collision in the head-on scenarios than when traveling 250 knots. Thus, pilots may have allowed for a much lower tCPA value in the 150 knot conditions without feeling less safe. The results regarding ownship speed affecting ATPs more with manned versus unmanned intruders may have to do with ATPs expectation of UAS reaction time and abilities. They may perceive these automated machines as being able to potentially react more quickly and maneuver in a more agile manner than manned aircraft can.

The main effects observed with the tCPA metric were found with intruder approach angle, and ownship speed just as was seen with the dOWN metric. However, the tCPA metric showed no main effect with background traffic level as the dOWN metric did. This is not surprising, since the dOWN metric was measured more precisely due to less rounding and finer incremental units (tens-of-thousands of feet versus rounded whole-seconds) and because it just made the cutoff for dOWN significance ($p = .045$ out of .05).

Although the differences in the tCPA metrics for all independent variables are consistent with differences observed with the dOWN metric, they do shine light on an important factor. Opposite of the dOWN metric, the tCPA metric showed the highest degree of variability in the intruder angles approaching from the rear of ownship. Inversely, intruders approaching from angles in front of ownship displayed a low degree of variability (as in the difference from angle to angle in tCPA values). Again, this pattern of variability may be vital in comprehending how the WCB is perceived. Pilots may consider metrics they can easily interpret on a traffic display as their primary indicators for   determining the WCB, even if that means using different metrics given different intruder approach angles surrounding ownship.

Subjective Questionnaire Responses. Responses about WCB perception unveiled that pilot’s think of the WCB as a factor of distance, time, or both overall. This is logical since closure rate is a result of time and distance relationship. However, more than double the percentage of GA pilots primarily thought of the WCB as a measurement of distance compared to ATPs, while almost double the percentage of ATPs thought of the WCB in terms of time, or combination of time and distance than GA pilots did. This sharp contrast could again be due to differences in flight environments each pilot type is used to. GA pilots move slower and have more time to deal with potential conflicts, more often using distance as a mental model for separation since their speed and distance values are relatively smaller. ATPs move faster and therefore quantify aircraft separation more easily by time since distance and speed values are so great.

In terms of what affected the WCB opinion the most, closure rate was the biggest subjective factor, considerably more so than intruder angle or aircraft maneuverability. This was the case for both pilot types. Across the board, pilots believed the WCB to be different from other similar terms (mentioned above in section entitled “Similar Terms and Concepts”) primarily because it subjectively varies as other definitions do not. Surprisingly, over half of overall pilot and between pilot type responses showed they were comfortable with the current definition of Well Clear. This may be because pilots like self-separating under their own jurisdiction to take into account the variability of the current Well Clear interpretation. Since the current study only considered lateral WCB, when asked what the vertical component of WCB should be over 70% of overall pilots thought it should be 1000 feet vertical separation, with ATPs split in their want for 1000 feet and being greater than 1000 feet. The majority of GA pilots agreed upon 1000 feet. 1000 feet is the standard vertical separation margin for most instances in controlled airspace, so no surprise here since it has been an effective margin for years. All pilots strongly agreed that ownship speed affected WCB dimensions, which aligns with the statistically significant effect of ownship speed effect on WCB. Pilots moderately agreed that background traffic density affected the WCB, which also parallels with the statistical findings of traffic level effect on WCB.

The next set of questions was asked to study intruder type differences. When asked if UAS should abide by the same WCB as manned aircraft, there was almost a 50/50 split in responses. Overall almost half of the pilots said yes, while just under half said no. Interestingly, GA pilots provided slightly more yes answers while ATPs answered more no's. This could possibly be because GA pilots averaged a younger age, and have spent more of their adolescence surrounded by more intelligent and reliable computer systems then their ATP counterparts, allotting more trust in UAS while ATPs have seen many upgrade iterations in their cockpits and witnessed the success and failures of them all first hand. Also, ATPs typically have more lives at stake when they fly perhaps giving reason to their decreased UAS trust.

When asked about arousal (i.e. stress level) differences between intruder types, over 70% of all pilots answered they experienced no difference, while 30% or less experienced more stress with UAS intruders. This is an important finding because it indicates a fairly large portion of pilots may feel uncomfortable or more stressed with UAS traffic encounters, which is something the FAA must take into account during integration. The most threatening overall intruder angle was mostly felt to be from head-on approaches. This was followed by right/left directions, and trailed by overtake (rear) directions. This is logical and follows suit with the hierarchy of closure rates across intruder angles.

When asked about perceived safety levels between intruder types, overall pilots felt much safer with manned intruders than UAS. However, GA pilots appeared to feel slightly safer with UAS than ATPs did. Conversely, , when asked to rate perceived trust levels between intruder types, although overall pilots trusted both manned and UAS evenly, GA pilots had generally higher trust and showed slightly higher ratings for manned intruder trust than UAS. These findings not only show how spread out the opinion of manned versus UAS traffic can be, but also shows GA pilots vary more in their opinion than the ATPs. This must be taken into account when integrating UAS into the NAS, as different classifications of airspace may have different WCBs depending on which pilots consist of the majority in that given airspace.

UAS specific questions were asked to uncover more information on UAS interaction. When asked if UAS could autonomously abide by the current WCB definition, over half of all pilots and pilot types said no. But, there was a higher yes answer percentage for GA pilots over ATPs, again displaying the overall trend of GA pilots having more faith in UAS than ATPs did. Since all trials involved at most only one UAS intruder, when asked if their WCB would change if two or more UASs were involved overall half of the pilots said no. However when broken down by pilot type over 80% of GA pilots said no, while almost 60% of ATPs said yes. This is trend seems opposite of previous mentioned higher GA trust in UAS, and yields the need for further exploration of how multiple UAS interactions would affect the WCB. Finally, when asked how they felt about UAS integration, most pilots answered safe if proven. This answer was closely followed by unsafe feelings, believing UAS integration complicates things. More

ATPs answered the latter response in this question than GA pilots, representing the common trend of higher GA trust with UAS again.

The next set of questions were asked to find opinion of how our lab's version of a CDTI, our CSD, and other CDTIs would affect WCB perception. Although nearly 90% of the GA pilots did not have any experience with a CDTI, most ATPs did and they mainly had experience with the Traffic Collision Avoidance System II (TCAS II) that is largely used in airlines. For ATPs, when asked if their current display was adequate for WCB perception, more than half said yes, but just over 40% said no. Pilots were also asked if they envisioned themselves primarily utilizing a CDTI or out-the-window view to maintain WCB, and across the board most answered they would use a CDTI. As most ATPs use a CDTI today anyway, this is not surprising. Overall, all pilots agreed that our lab's CSD had a positive impact on WCB perception compared to their current CDTI or other detection method.

The final set of subjective questions asked ATPs if they believed pilots with less experience, and GA pilots if they believed pilots with more experience would have different opinions of the WCB. All ATPs but one agreed yes to the question, while GA pilot opinion varied with most responses saying yes and an equally split response rate between no and maybe. This again displays the uniformity of ATP opinions while GA pilots tend to have a more diverse thinking process perhaps due to their lesser flight experience and perhaps less uniform training.

After all other data collection was complete, subjective WCB drawings were completed. Half of all pilots depicted a greater distance in front of ownship with less distance in their drawings.   Slightly more GA pilots drew g this shape than ATPs. This general shape was closely followed by circular WCB drawings with ownship equidistant from all WCB points regardless of the angle. However, ATPs showed a nearly 50/50 split between the greater in front, less in rear and the circular depictions. The other category consisted of very few WCB drawings and displayed some peculiar shapes which prove difficult to classify.

Future Research Recommendations

Future research should be conducted to properly determine how pilots perceive the WCB, and should include additional metrics to uncover increased breadth and depth in the definition of this construct. Vertical WCB should be included since it is a highly dynamic factor requiring careful research.   It can change everything about potentially altering the WCB dramatically if intruding aircraft ascend or descend at rapid rates from different approach angles. Investigating the effects of multiple instead of just single UAS intruders would be crucial to UAS integration into the NAS, as UAV usage will only continue to increase and imminently yield high density UAS environments. This research only considered 8 intruder approach angles, and increasing this number of angles to 16, 32, or more could provide a picture of higher WCB fidelity and would be extremely valuable. Also, examining how the WCB is affected by more dynamic flight environments (as this research only took place in optimal conditions) such as crosswinds and weather phenomena, as well as more complex airspace such as class B, C, or D airspace (as this research took place in class E, or uncontrolled airspace) would be of great worth since pilots often deal with non-optimal and busy conditions. Finally, it would be important to measure UAS pilot perspective of the WCB, as they are more removed from the situation than the manned aircraft pilots in this research. Their WCB opinion would help contrast differences in manned versus UAS perception and could uncover issues before they arise in a real world setting.

Conclusion

The purpose of this thesis research was to determine how different pilot types perceived the Well Clear Boundary, and to observe if the WCB changed when dealing with manned versus unmanned aircraft. This research was successful in addressing the research questions, finding several significant main effects and interactions. It is vital to realize that the findings in this research were all for pilots in a part task environment, without them preforming the primary task of flying as they normally would. While flying, utilizing a CDTI as they did in this study would be a secondary task in real-world scenarios, therefore potentially changing WCB results. This fact does not degrade the current research, as these findings lay the framework for human perception of the WCB in a simple experimental setting despite lacking the complexity that real flying involves.

The first research question attempted to uncover what the WCB is for civilian pilots. We now have objective metrics for the subjective concept of Well Clear. The next question revolved around determining the perception of the WCB and if it differs between General Aviation pilots and Commercial ATPs. The answer is yes; the effect of intruder type depends on ownship speed, and that differs across pilot type when measured by dOWN. It was also asked if the WCB differs when pilots interact with manned versus unmanned aircraft. It was found that the effect of intruder type depends on traffic level and ownship speed, and that effect differs across intruder approach angles when measured by tCPA. This research also revealed that the effect of intruder type depends on traffic level which differs across ownship speeds when measured in tCPA. In terms of what other parameters affected the perception of WCB, it was found that the effect of ownship speed depended on intruder approach angle when measured in dOWN. There were also several main effects evident. dOWN measurements displayed main effects with ownship speed, intruder angle, and background traffic level, while tCPA main effects were observed with ownship speed and intruder angle.

Subjective findings uncovered an important trend, that even though GA pilots indicated a larger average WCB, they tended to rate UAS aircraft with higher trust and safety ratings than ATPs did. GA pilots also appeared to have more diverse responses than ATPs did, where ATPs had more similar and uniform language in their answers. These subjective findings indicate fundamental differences in pilot experience levels, showing how their perceptions may differ based on hours and type of flight environment flown. Subjectively, it is also important to note how broad the opinion of not only the WCB, but interaction with manned versus unmanned intruders was across all pilots and between pilot types. Many different mental models and opinions were observed, which may demonstrate the need for more structured and less subjective definitions of aviation concepts, especially when it comes to aircraft spacing procedures.

The most important overall conclusion to draw from this research is based on the objective results. Pilots likely perceive the WCB in terms of what is most easily recognizable and/or mentally computable based on the angle of approaching intruders. As previously mentioned, the metrics of dOWN and tCPA seemed to mirror each other over the horizontal axis with dOWN having larger distance variation between angle values in front of ownship while tCPA had larger variation in angle values in values to the rear of ownship. Therefore, it is reasonable to assume that since uniformity (i.e. least value variation) of the WCB is most evident to the rear for distance based measurements and to the front for time based measurements, that pilots perceive the WCB like the model below in Figure 29:

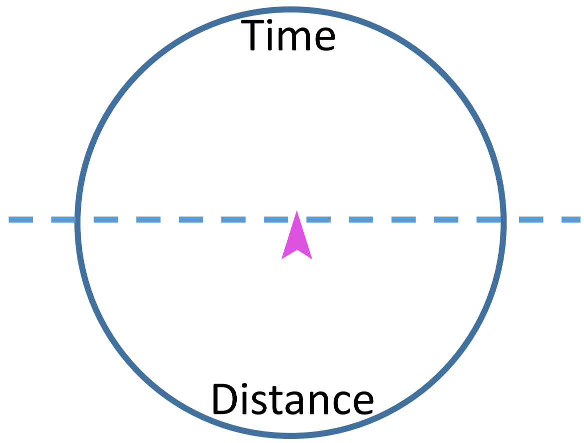

Figure 24. Pilot WCB Perception – Time in Front and by Distance to Rear

Since the rear of ownship experiences a low closure rate with low distance and high time to collision values, distance may be easier and quicker to mentally calculate for pilots. Conversely, to the front of ownship where a high closure rate with large distances and low times are evident, time may be easier and quicker to mentally calculate for both pilot types. This finding is supported objectively and subjectively in the data and is instrumental in the future integration of UAS into the NAS. It would mean that in defining the WCB for manned aircraft, pilots are more comfortable knowing time separation in front and distance separation to the rear. Therefore pilots may better perform separation procedures knowing specific types of intruder information depending on relative angle surrounding their aircraft, as opposed to a static and finite WCB metric encircling them. Beyond the concerns of the WCB, this data can also be used to help ATC better understand pilots’ perception of intruders encroaching their airspace, improving their aircraft spacing tactics by advising pilots using angle and metric combinations that they can most efficiently comprehend.

To compare the current findings to other proposed WCB definitions mentioned in the introduction, it is important to consider that the current research was only concerned with measuring the WCB in the lateral plane of three-dimensional space. Other proposed definitions were generated without ignoring the vertical plane dimensionality, therefore potentially allowing for smaller WCB's since an additional dimension of space is available for pilots to maneuver in (i.e. diving or climbing around an intruder). With that in mind, Figure 1 depicts a tCPA WCB having a larger area in the front of ownship, and a smaller distance-based WCB encircling ownship. This definition incorporates distance and time, giving different shapes for each metric. Similar concepts to the present research are evident, and it can be observed that the Figure 1 definition recognizes the need to have different WCB based on using time or distance. Figure 2 depicts two Tau values (range and vertical tau) that when combined amount to a positive numerical value when intruders converge with a UAS, and a negative value upon their divergence, representing an approximation of time to CPA or tCPA. These tau values incorporate elements of distance and time, but blend the two metrics together mathematically. The current findings indicate that combining metrics is useful for human pilots depending on directionality, however this Figure 2 definition was developed for UAS aircraft only which is why combining metrics mathematically is acceptable for the UAS on-board computers and sense and avoid capabilities. Also, the Figure 2 equations only work in the case of a direct collision course with a straight line of intersection. While this research procured WCB measurements that were only tested with straight line intruder intersections, these measurements are applicable to curved intersection paths as well.

Comparing the present research's WCB to the proposed definition in Figure 3 known as "Ellipsoid defined by Tau with tapered vertical separation," it uses a tapered vertical separation to avoid "nuisance" alerts resulting from intercepting aircraft that may have enough vertical separation to properly evade each other, but still cause alerts. This model is difficult to compare to the present research due to the heavy influence of vertical tapered separation, however in Figure 3 the attempt to incorporate elements of distance and time are present by the arrows indicating adjustment for closure rate (which is a time based metric) as well as the horizontal protection (a distance based metric). Finally, to compare this research to the MIT model in Figure 4, their model was entirely distance based. However, the model is similar to this research since it uses real data generated from actual pilots, and is concerned with manned-ownships only. What sets it apart (aside from having a distance metric only) is it does not take into account any encounters involving manned and UAS together. Having said that, the tear-drop shape it depicts (lager distance in front of ownship, smaller in the rear) mirror very closely to what this research measured when considering the overall WCB shape. Also, the size of the MIT WCB shown in Figure 4 is much smaller than what this research measured, with theirs extending out in excess of only 8,000 feet compared to the 35,000 seen here in front of ownship.

The current thesis research has provided scientific data on the perception of Well Clear, as well as how that differs across pilot types and manned versus unmanned intruders. This could be considered by comities, research initiatives, and regulatory bodies that are currently contributing to the NextGen airspace infrastructure. This is because current resources that provide guidance and make decisions on the issue of Well Clear such as SC 228, various FAA resources including the Airman's Information Manual, Advisory Circulars, FAA library articles, as well as research entities like MIT and other universities have rarely considered the human pilot opinion in the matter. They have tended to base separation standards off of ATC preferences, FAA traffic data, and subject matter expertise (FAA, 1983; FAA, n.d.; FAA, 2014; Weibel, Edwards, & Fernandes, June, 2011). These are all vital and well established sources, yet they often lack the principles and findings of Human Factors science, as well as the perceptional preferences among different pilots interacting with varying technologies.

With present UAS regulations, incidents of UASs technologies crashing and colliding with manned aircraft (Reed, 2011; The Washington Post, 2014; Drone Wars UK, 2013) have been witnessed. UAS integration into the NAS will also be an even bigger issue for GA pilots, as they deal with less aviation technology, less experience levels, rely more heavily on visual avoidance procedures, and are allowed more flight path freedom than ATP pilots operating in commercial airlines (Goyer, 2012). Therefore, this thesis data can assist in making future decisions about Well Clear definitions regarding multiple pilot types, and can help decisions about UAS operational parameters when flying in close proximity to other manned aircraft by providing quantitative human pilot perception and qualitative insight on the matter.

If pilots' mental models truly follow the rationale suggested by this research, future sense and avoid systems aboard UAS as well as traffic collision avoidance systems need to consider these human factors findings. Perhaps UAS could gain higher acceptance and trust ratings if they are able to provide this approach-angle-relevant information, as well as intruder intent information such as upcoming route changes, to manned pilots sharing their airspace. Through this, we can best design technology around the needs of human operators in order to prevent confusion, mistrust, and accidents in our airspace given the increase of air traffic that is projected. This research can contribute to creating a more efficient, intelligent, and most of all safer environment for tomorrow's airspace.

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Appendix A: San Jose State University IRB Approval

SAN JOSÉ STATE
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Division of Academic Affairs

Associate Vice President
Graduate Studies & Research

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To: Joseph T. Ott

From: Pamela Stacks, Ph.D.
Associate Vice President
Graduate Studies and Research

Date: March 14, 2014

The Human Subjects-Institutional Review Board has approved your request to use human subjects in the study entitled:

"Well Clear: General Aviation & Commercial Pilots' Perception of UAS vs. Manned Aircraft NAS"

This approval is contingent upon the subjects participating in your research project being appropriately protected from risk. This includes the protection of the confidentiality of the subjects' identity when they participate in your research project, and with regard to all data that may be collected from the subjects. The approval includes continued monitoring of your research by the Board to assure that the subjects are being adequately and properly protected from such risks. If at any time a subject becomes injured or complains of injury, you must notify Dr. Pamela Stacks, Ph.D. immediately. Injury includes but is not limited to bodily harm, psychological trauma, and release of potentially damaging personal information. This approval for the human subject's portion of your project is in effect for one year, and data collection beyond March 14, 2015 requires an extension request.

Please also be advised that all subjects need to be fully informed and aware that their participation in your research project is voluntary, and that he or she may withdraw from the project at any time. Further, a subject's participation, refusal to participate, or withdrawal will not affect any services that the subject is receiving or will receive at the institution in which the research is being conducted.

If you have any questions, please contact me at (408) 924-2427.

Protocol # S1402043

cc. Kevin Jordan 0120

Appendix B: NASA Ames Informed Consent

ARC - 475 - Category II Participant Consent Form

To the research Participants: Please read this consent form and the attached protocol and/or subject instructions carefully.

A**. I agree to participate** in the Well Clear: General Aviation and Commercial Pilots' Perception of Unmanned Aerial Systems (UAS) VS. Manned Aircraft in the National Airspace System (NAS) research experiment as described in the attached protocol or subject instructions. I understand that I am employed by _________________________ who can be contacted at ______________________________________.

B**. I understand that my participation could cause me minimal risk*, inconvenience, or discomfort.** The purpose and procedures have been explained to me and I understand the risks and discomforts as described in the attached research protocol.

C. **To my knowledge**, I have no medical conditions, including pregnancy that will prevent my participation in this study. I understand that if my medical status should change while I am a participant in the research experiment there may be unforeseeable risks to me (or the embryo or fetus if applicable). I agree to notify the Principal Investigator (PI) or medical monitor of any known changes in my condition for safety purposes.

D. **My consent to participate has been freely given**. I may withdraw my consent, and thereby withdraw from the study at any time without penalty or loss of benefits to which I am entitled. I understand that the PI may request my withdrawal or the study may be terminated for any reason. I agree to follow the procedures for orderly and safe termination.

E**. I am not releasing NASA** or any other organization or person from liability for any injury arising as a result of my participant in this study.

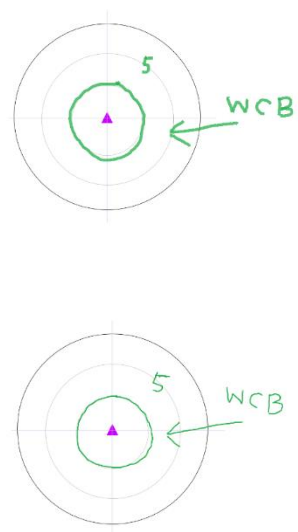
F. **I hereby agree that all records collected by NASA in the course of this study are available** to the research study investigators, support staff, and any duly authorized research review committee. I grant NASA permission to reproduce and publish all records, notes, or data collected from my participation, provided there will be no association of my name with the collected data and that confidentiality is maintained, unless specifically waived by me. While all stated precautions will be taken to protect anonymity, there is a small risk that some or all of the participants' data could become identifiable.

Participant Signature: ____________________________ Date: _________________

Appendix C: Subjective WCB Map Drawings

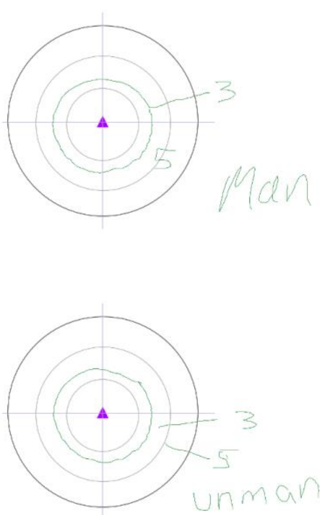
Note – top drawing is for manned intruders, while the bottom is for unmanned intruders.

Pilot 01 - GA



Pilot 03 - ATP

Pilot 02 - GA



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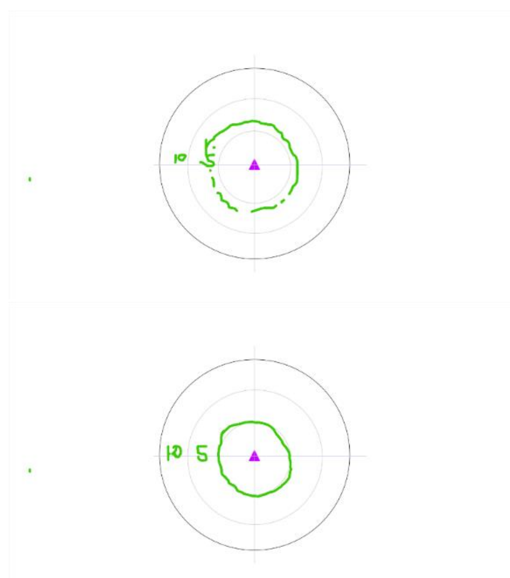
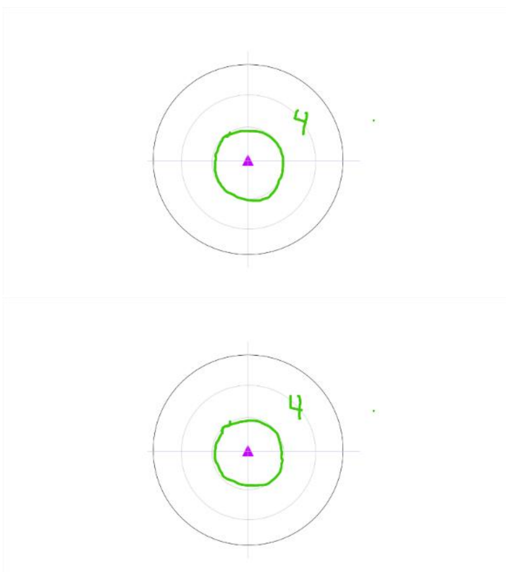


Pilot 05 - ATP

Pilot 07 - GA

Pilot 06 - GA



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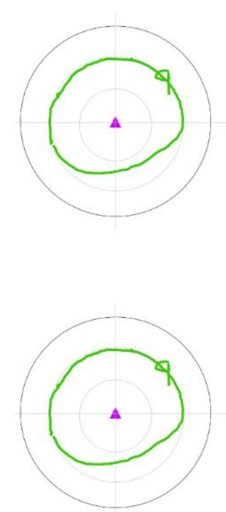

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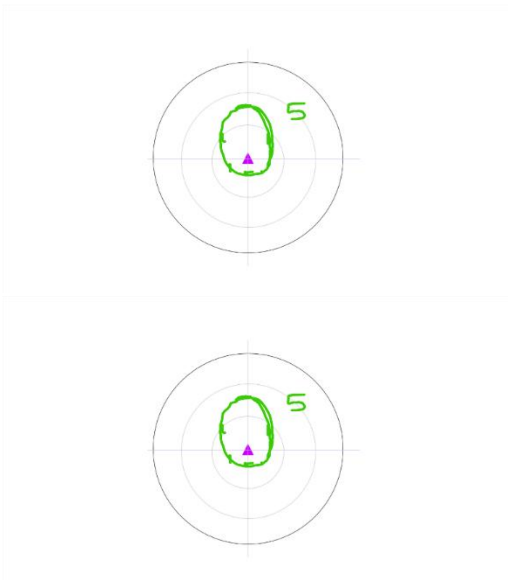
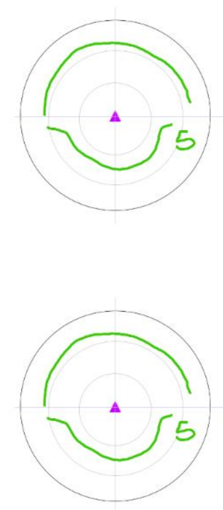
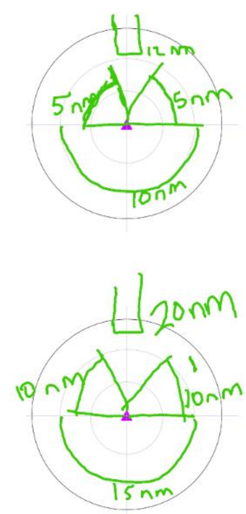


Pilot 11 - GA

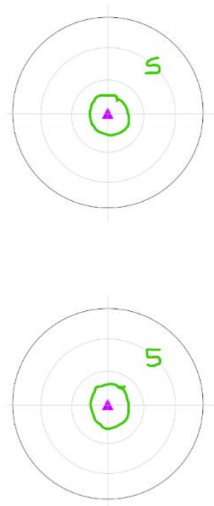


Pilot 10 - ATP

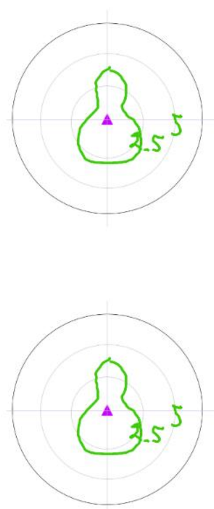
Pilot 12 - GA



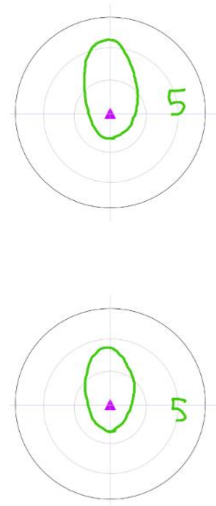
Pilot 13 - ATP



Pilot 14 - GA



Pilot 15 - GA



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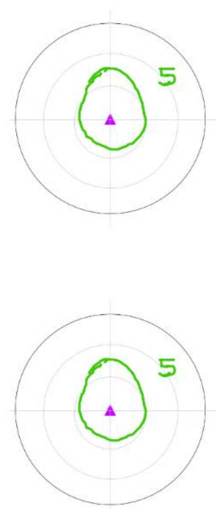

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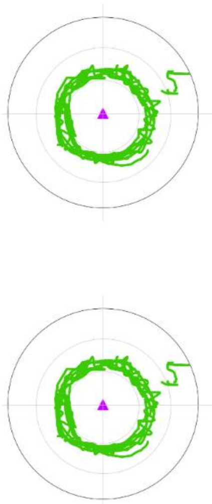
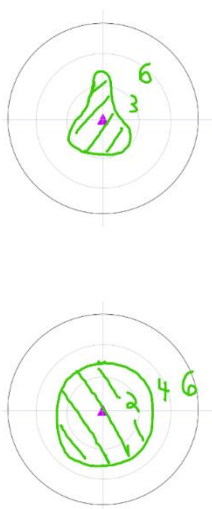
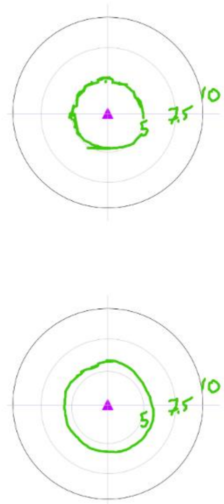


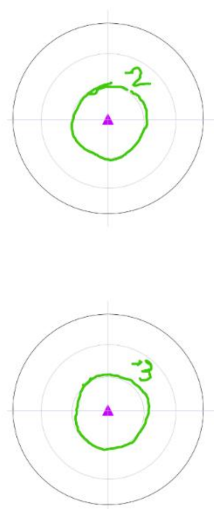
Pilot 18 - GA



Pilot 19 - ATP



Pilot 20 - ATP



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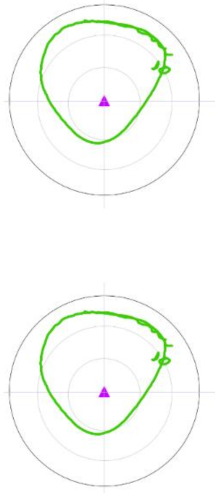
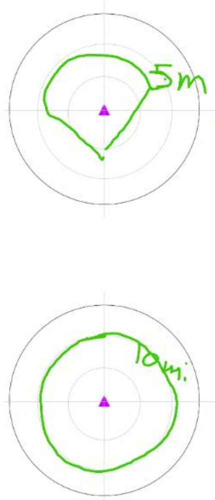


Pilot 22 - GA



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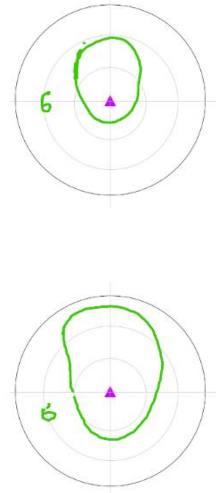

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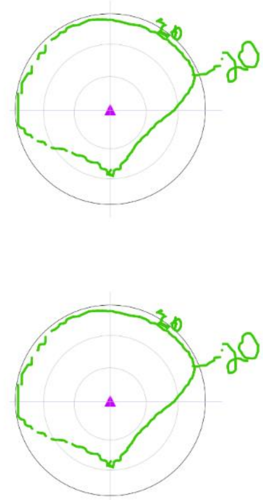

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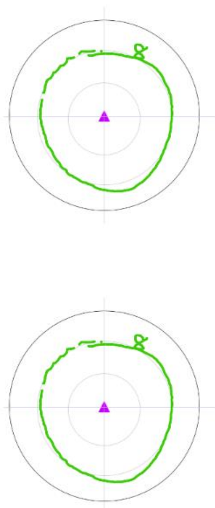

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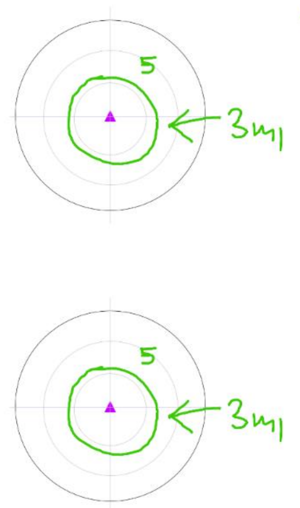

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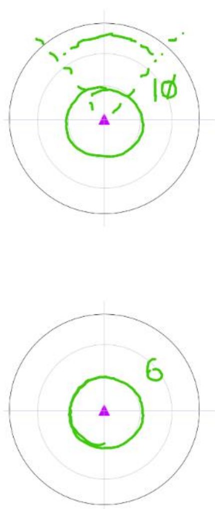

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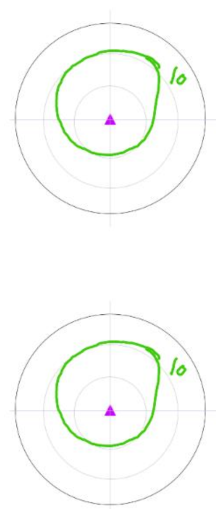

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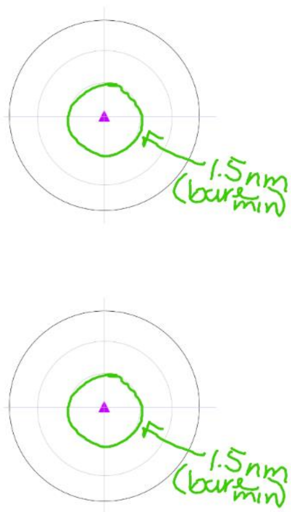

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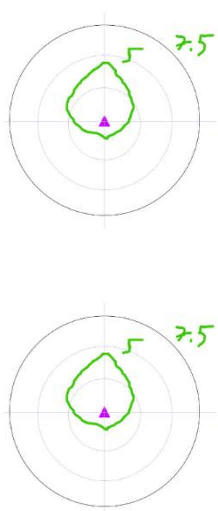

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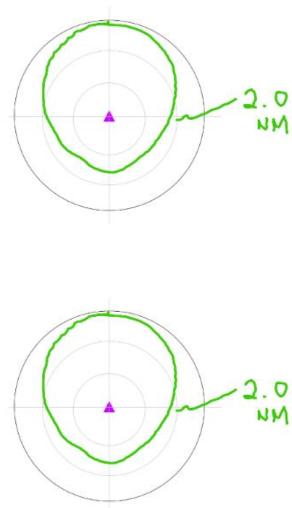

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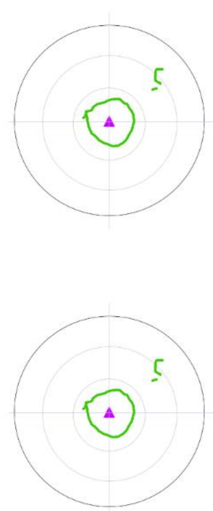

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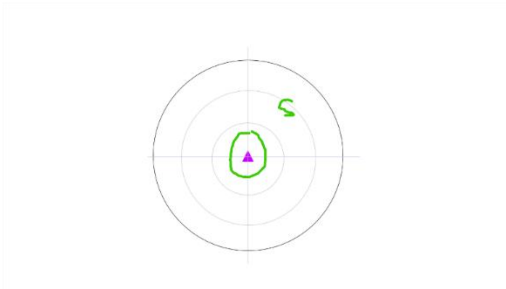

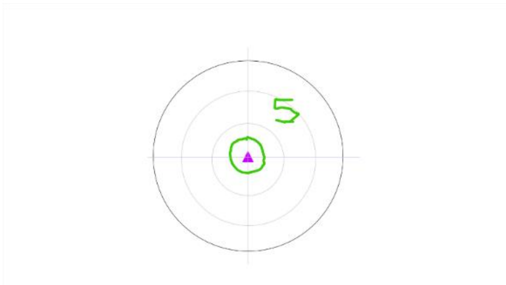

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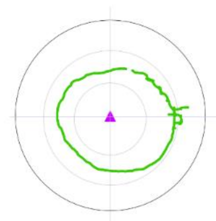
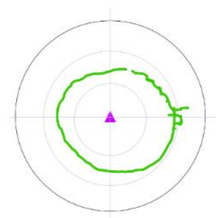




Appendix D: Post-Simulation Pilot Questionnaire

1. What unit of measurement do you first think of when measuring the well clear boundary (WCB) from ownship position? (I.e. Do you think of it as a measure of time before collision? Or distance before collision? Another unit of measurement?)

2. Do you believe that unmanned vehicles should abide to the exact same WCB as manned vehicles if you were flying a manned aircraft in the skies? Why or why not?

3. What affects your opinion of the WCB the most? Please explain why you feel this way.

4. What strategies did you use in determining the WCB?

5. How do you believe WCB to be different from Legal Separation? From other similarly defined terms?

6. Did you experience any difference in arousal (i.e. stress levels) when interacting with the Manned Vs Unmanned intruders?

7. Do you feel comfortable with the current definition of WC?
    a. Do you feel confident that the UAS can abide by this definition autonomously?

8. All scenarios with UAS intruding aircraft only involved one UAS vehicle per each trial. Would your opinion of the WCB change if there were 2 or more UASs involved instead of just one?

9. All scenarios involved two-dimensional interaction with intruders (in the horizontal plane). What would your opinion of the WCB in the vertical plane be? (Feel free to draw a depiction or describe it as best you can)

10. How do you feel about in terms of the safe integration of UAS's into our national airspace system? Please thoroughly explain your response.

11. For this experiment, you used our Cockpit Situational Display (CSD) as a Cockpit Display of Traffic Information (CDTI). What system (if any) do you primarily use as a CDTI?
    a. Do you feel that your current CDTI system display is adequate enough to allow you to safely perceive the WCB around ownship? Why or why not?

12. What, if any, changes would you make to your display technology to better assist you in determining the WCB?

13. What direction did the intruder feel most threatening from (made you feel most vulnerable to collision)? Please explain why you felt this way.
    a. Note – please refer to intruder directions in terms of cardinal directions (N,W,E,S) from ownship, as if ownship were always facing North (0 or 360).

Response for interactions with **Manned** intruder Aircraft:	
Response for interactions with **Unmanned** intruder Aircraft:	

14. Would you envision yourself more often relying on a CDTI to maintain the WCB boundary, or out-the-window view? (Note – only referring to horizontal separation, not vertical)

Response for interactions with **Manned** intruder Aircraft:	
Response for interactions with **Unmanned** intruder Aircraft:	

15. What was your perceived level of safety during interaction with intruding aircraft?

Response for interactions with **Manned** intruder Aircraft:	
Response for interactions with **Unmanned** intruder Aircraft:	

16. Did you feel speed of ownship changed your perceived dimensions of the WCB? (circle one)

Strongly Disagree Disagree Neutral Agree Strongly Agree

17. Do you believe that traffic density in your immediate surrounding airspace affected your perception of WCB?

Strongly Disagree Disagree Neutral Agree Strongly Agree

18. Do you feel that the CSD had a positive impact on your WCB perception in comparison to your current CDTI?

Strongly Disagree Disagree Neutral Agree Strongly Agree

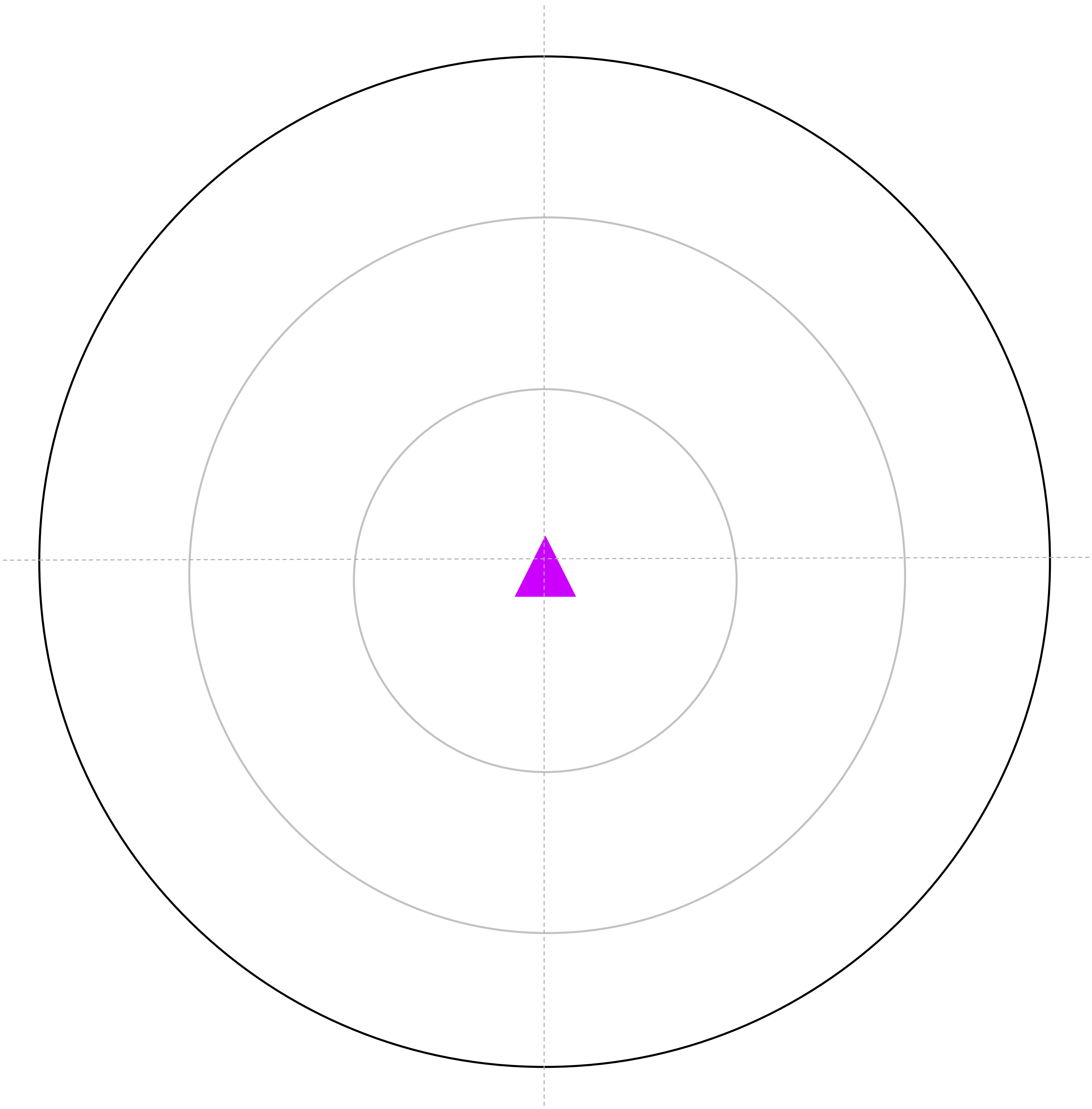
19. Please rate the overall trust level you felt towards the intruding aircraft (circle one)

Response for interactions with **Manned** intruder Aircraft:	Very Low Trust · Low Trust · Neutral Trust · High Trust · Very High Trust
Response for interactions with **Unmanned** intruder Aircraft:	Very Low Trust · Low Trust · Neutral Trust · High Trust · Very High Trust

20. FOR GA PILOTS ONLY - Do you believe pilots with more experience than you would have a different opinion of the WCB? If so, why?

21. FOR COMM PILOTS ONLY – Do you believe pilots with less experience than you would have a different opinion of the WCB? If so, why?

22. Please draw your interpretation of what the WCB should be between your ownship and other **Manned** aircraft. Be sure to indicate a range scale as you see fit.



23. Please draw your interpretation of what the WCB should be between your ownship and other **Unmanned** aircraft. Be sure to indicate a range scale as you see fit.