# Assistive Detect and Avoid for Pilots in the Cockpit

Víctor A. Carreño
*Compass Engineering*
San Juan, PR, USA
victor.carreno@ymail.com

Paolo Masci
*National Institute of Aerospace*
Hampton, VA, USA
paolo.masci@nianet.org

María Consiglio
*NASA Langley Research Center*
Hampton, VA, USA
maria.c.consiglio@nasa.gov

***Abstract*—Aircraft not receiving radar services rely on see and avoid and radio coordination via Common Traffic Advisory Frequencies to remain well clear of each other and avoid mid-air collisions. Radio coordination is usually performed in the vicinity of non-towered airports whereas non-radar services en-route operations rely solely on see and avoid. This paper presents the results of a simulation study of the effectiveness of assistive detect and avoid technologies when used to enhance pilots' ability to see and avoid nearby traffic. Three different experimental conditions are modeled, representing "unaided see and avoid", "see and avoid with traffic advisories", and "see and avoid with assistive detect and avoid technology". The effectiveness of see and avoid is evaluated using a set of head-on, crossing, and overtaking encounter scenarios and a model of visual acquisition embedded in a Monte Carlo simulation. The effectiveness of assistive detect and avoid is estimated for the same encounter scenarios. A prototype system for detect and avoid and a summary of results are presented. Preliminary results strongly suggest that assistive detect and avoid could greatly enhance the capabilities of flight crews to avoid traffic and remain well clear.**

***Keywords—collision, detect and avoid, resolution, well clear, surveillance***

## I. Introduction

This paper describes a fast-time simulation study of the effects of assistive Detect and Avoid (DAA) technology on the potential reduction of conflict severity and mid-air collisions when see and avoid is the only means of conflict avoidance. The Code of Federal Regulations requires that vigilance is maintained by each person operating an aircraft to see and avoid other aircraft, regardless of the type of operation. Many Visual Flight Rules (VFR) operations depend on see and avoid as the only means of remaining well clear of traffic aircraft.

The simulation study described in this paper evaluates severity of conflict encounters in three different experimental conditions: Unaided see and avoid, see and avoid with traffic advisories, and see and avoid with assistive DAA technology. A visual acquisition algorithm is used to calculate the probability of a pilot visually acquiring traffic for a set of head-on, crossing, and overtaking encounters.

The fast-time simulation includes a virtual pilot component designed to model the expected pilot's behavior in response to potential traffic conflicts using either visual acquisition (aided or unaided) or input from the alerting and guidance module. The virtual pilot's configuration parameters include the pilot response delay and preference of maneuver, among others. It also incorporates a set of heuristics that include: 1. The right-of-way rules as specified in the Code of Federal Regulations; 2. Assessment of the viability and efficiency of the guidance; 3. A vertical speed bias which favors a climb when the aircraft track is west (180 to 359 deg) and a descent when the aircraft track is east (0 to 179 deg); 4. A change of type of maneuver (vertical to horizontal) when a commanded maneuver is ineffective in solving a conflict as the scenario evolves.

The simulated encounter scenarios are evaluated using a conflict severity metric developed by RTCA Special Committee SC-228 for Unmanned Aerial Systems (UAS) [1]. The severity metric consists of a protected volume defined as a cylinder of a given diameter and height, and a dynamic component which accounts for distances and closure rates between the aircraft.

## II. Visual acquisition probability

The procedure of see-and-avoid to remain well clear of traffic aircraft and avoid collisions involves the following steps:

1. The pilot/flight crew visually scans the airspace for traffic aircraft
2. The pilot/flight crew visually acquires the traffic
3. The pilot/flight crew determines if the traffic is a threat and if any action is needed to remain well clear
4. The pilot/flight crew formulates the best action to take
5. The pilot/flight crew executes an avoidance maneuver

The first and second steps of this process are modeled using a visual acquisition probability algorithm based on an MIT Lincoln Laboratory algorithm developed in the 1980's [2]. The algorithm calculates the cumulative probability of visual acquisition for a given time and aircraft states. The probability of acquisition depends on the size of the target aircraft, the speeds, the visibility, the encounter angle, whether the target has been "pointed" to the flight crew, and several other parameters. A "pointed" target refers to a target which the crew has been made aware of but he/she has not visually acquired yet. This alert can be an Air Traffic Control traffic advisory or a position report from the traffic aircraft through a Common Traffic Advisory Frequency. An example of a traffic advisory is "N123 you have traffic at 2 o'clock, 3 miles, same altitude,

Work funded by the National Aeronautics and Space Administration.

a Bonanza." An example of a traffic report is "Williamsburg traffic, Skyhawk N123 five miles south-west of the field descending through 4,200 inbound for runway 13, Williamsburg traffic." An encounter where the flight crew has been made aware of the target aircraft is referred to as aided visual acquisition.

### A. *Cumulative probability*

The visual acquisition algorithm calculates the probability from minus infinity to time *t* for a given encounter. An encounter can be represented by a sequence of 1-second steps. In Figure 1, the node $\bar{s}_N$ represents the state where no visual acquisition has occurred at time $t = N$ and the node $s_N$ where visual acquisition has occurred. CPA is the Closest Point of Approach, or the moment when the horizontal range is minimum.

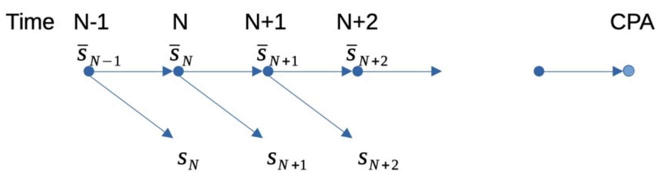


Fig 1. Visual acquisition probability tree

The cumulative probability at time $t = N$ is given by,

$$P_N(acq) = \sum_{i=-\infty}^{N} P(s_i) \tag{1}$$

The visual acquisition probability algorithm can be used in Monte Carlo encounter simulations to statistically calculate when a flight crew will acquire, react, and maneuver in an encounter and the severity of such encounter. The probability of visually acquiring traffic in any given 1-second interval (conditional probability) can be obtained from the cumulative probability as described in the next section.

### B. *Visual Acquisition Probability in a 1-second interval*

Let $A_N$ be the event in which the flight crew visually acquires the traffic aircraft in the interval *N-1* to *N*. The probability of event $A_N$ is the conditional probability that, given state $\bar{s}_{N-1}$, it will transition to state $s_N$,

$$P(A_N) = P(s_N \mid \bar{s}_{N-1}) = \frac{P(s_N \cap \bar{s}_{N-1})}{P(\bar{s}_{N-1})} \tag{2}$$

The numerator and denominator probabilities in equation (2) can be obtained from the cumulative probabilities,

$$P(s_N \cap \bar{s}_{N-1}) = P_N(acq) - P_{N-1}(acq) = \sum_{i=-\infty}^{N} P(s_i) - \sum_{i=-\infty}^{N-1} P(s_i) \tag{3}$$

$$P(\bar{s}_{N-1}) = 1 - P_{N-1}(acq) = 1 - \sum_{i=-\infty}^{N-1} P(s_i) \tag{4}$$

From equation (2), it is possible to develop a simulation where for each 1-second step the probability of visually acquiring the traffic aircraft is calculated. If the flight crew does not acquire the traffic aircraft, the trajectories continue unaltered to the next step. If the flight crew acquires the traffic, a virtual pilot in the simulation will maneuver to remain well clear or to regain well clear if it has been lost. More details of the Monte Carlo simulation are presented in Section V.

## III. Detect and Avoid

Detect and Avoid (DAA) is defined as "the capability of an unmanned aircraft to remain well clear from and avoid collisions with other airborne traffic" [3], and was developed to provide remote pilots of unmanned aircraft an alternative means of compliance with see and avoid regulations. DAA systems use sensors such as radars, lidar, electro-optical cameras, and Automatic Dependent Surveillance (ADS), among others, to determine the location and velocity vector of a traffic aircraft. Based on the projected trajectories of the aircraft, the DAA system determines if a conflict exists, and computes possible resolution maneuvers to prevent collisions. The DAIDALUS algorithm [4], used in this study, is the reference implementation for the DAA Minimum Operational Performance Standards (MOPS) document, DO-365, DO365A, and DO365B developed by the RTCA Special Committee SC228 [5].

DAA systems provide guidance to remain well clear of traffic by replacing a pilot's visual subjective judgment with a parametrically defined "well clear volume" (WCV) around each nearby traffic aircraft or "intruder". As such, DAA systems were developed for remote pilots commanding unmanned aircraft from a ground control station, the WCV configurations were chosen to ensure a desired target level of safety for the operational environment and vehicle performance characteristics of specific unmanned aircraft. Similarly, DAA pilot procedures were developed for remote pilots operating a ground control station. The alerting and maneuver guidance described in the DAA MOPS and generated by the DAIDALUS algorithm, consists of "colored bands" representing ranges of heading, vertical speed, horizontal speed, and altitude, as well as colored traffic symbols depicting different levels of alerts (more details are provided in Section IV).

### A. *Well clear volume and parameter sets*

The Well Clear Volume (WVC) is parametrically defined by a distance-based horizontal (DTHR), and vertical (ZTHR) thresholds, and by a time-based "closure time" (tau) threshold [5]. The DAIDALUS algorithm is fully configurable, enabling the implementation of different WCVs and different vehicle performance parameters.

For the results shown in Section VI, the following parameters have been used in the DAIDALUS algorithm:

Protected volume horizontal: 366 meters (1,200 feet)

Protected volume vertical: 137 meters (450 feet)

| | |
|---|---|
| tau: | 0 seconds or 35 seconds |
| Look ahead time: | 180 seconds |
| Alerting time: | 25 seconds |

These parameters do not represent any published WCV standards nor are they based on safety risk analysis. They were chosen for this simulation exercise because DTHR corresponds to the smallest TCAS II [6] protected volume at which a TCAS RA (Traffic Collision Avoidance System Resolution Advisory) may still be issued at low altitudes (so-called TCAS "Sensitivity Level 3"), specifically at altitudes between 1000 and 2350 feet above ground level such as when operating near airports. The time component tau was set to either 0 or 35 seconds (as opposed to 15 seconds).

## IV. DANTi: Detect and Avoid in the Cockpit

DANTi is a prototype Electronic Flight Bag which incorporates an assistive detect and avoid capability developed by NASA [7]. The notion of "assistive DAA" for manned aviation proposes the use of DAA technology to provide pilots traffic awareness and maneuver guidance support when required to comply with see and avoid regulations.

Assistive DAA technologies can be integrated into today's cockpit as "Non-Required Safety Enhancing Equipment" (NORSEE), as stated in the FAA Policy No: PS-AIR-21.8-1602, which describes a standardized approval process of NORSEE in general aviation (GA) and rotorcraft fleets [8].

The current DANTi prototype uses the NASA developed DAA-Displays library [9] for rendering the visual elements of the display and the DAIDALUS DAA algorithm to determine conflicts, generate alerts, and calculate resolution guidance. The DANTi prototype receives the ownship's and traffic positions and velocity vectors from a traffic surveillance source, such as an ADS-B (Automatic Dependent Surveillance-Broadcast) receiver and displays traffic alerts and resolution guidance to the flight crew. Figure 2 shows a depiction of the DANTi display on an electronic tablet.


Fig 2. DANTi display on an electronic tablet

In Figure 2, the following elements are shown:

1. Blue chevron at the center of the compass rose represents the ownship.
2. The hollow, white chevron represents a traffic aircraft. The number +01 indicates that the traffic is 100 feet above the altitude of the ownship. The down arrow indicates that the traffic is descending.
3. Ground speed of the ownship.
4. Heading of the ownship.
5. The display can be configured to display heading or track.
6. Altitude of the ownship.
7. Vertical speed of the ownship.
8. Scale of the display. 5.0 nautical miles to the outer ring.
9. Display could be configured for North up or track/heading up.
10. Display the call sign of the traffic aircraft (if available).
11. The moving map could be geographical, VFR charts, or other user selected data.

The display shows two peripheral bands, a heading band (12) and a speed band (13). The bands are peripheral because they are not in the current trajectory of the ownship. The heading peripheral bands shows that were the ownship to turn right to a heading between 113 and 158, it will be in conflict with the traffic aircraft. The peripheral speed band shows that were the ownship to decrease its speed to 40 knots or less, it will be in conflict with the traffic.

Figure 3 shows a display where the ownship is in a conflict trajectory with the traffic and it must maneuver to maintain well clear. These are called "corrective" bands.


Fig 3. DANTi display, current trajectory in conflict

The bands give the flight crew 6 resolution options, although not all options are desirable or valid. In the example of

Figure 3, the flight crew could slow down to 84 knots, turn right to a heading of 98 degrees, or descend at 1,400 feet per minute.

The Assistive DAA results shown in Section VI, tables 3, 4, 5, and 6, were produced with the virtual pilot configured to favor heading maneuvers. If heading maneuvers were not valid, then the virtual pilot will select vertical maneuvers and then horizontal speed maneuvers.

## V. Simulations

A fast time simulation framework was developed to evaluate the comparative conflict severity performance observed for the experimental conditions modeled in the study.

The block diagram in Figure 4 depicts the functional architecture of the simulation framework which is described below.

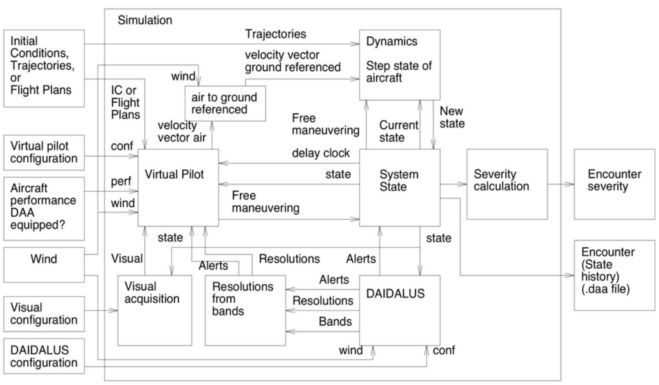


Fig 4. Fast-time simulation functional diagram

At a high level, this is a fast-time, time-stepping aircraft simulation in which aircraft encounters of (optionally) DAA equipped aircraft can be modeled to evaluate safety performance metrics.

- Input to the simulation includes the initial aircraft and wind conditions, the configuration parameters for the virtual pilot, the DAA equipage, and the visual acquisition model parameters.
- A point-mass dynamic model (Dynamics module in Figure 4) that uses the wind, positions and velocity vectors of the aircraft to simulate the aircraft trajectories.
- The visual acquisition algorithm which probabilistically determines if the flight crew has visually acquired the traffic at each time step.
- The DAIDALUS algorithm which determines if a conflict exists between the ownship and the traffic aircraft and generates DAA alerts and maneuver guidance.
- A virtual pilot that responds to DAA guidance to maneuver the aircraft when there is a conflict and generates headings, vertical speeds, and horizontal speeds. The virtual pilot will maintain the aircraft on their trajectories or flight plans when no conflict exists.
- A severity of encounter module that determines severity according to given criteria.

The simulation advances in 1-second steps and all modules are exercised in each step.

### A. *Conflict Severity Definition*

Conflict severity is defined using two methods:

- The Federal Aviation Administration, Air Traffic Organization, Safety Management System (SMS) manual [10]
- RTCA Special Committee SC-228 [1]

An excerpt of the severity table from Safety Management System (SMS) manual pertaining only to flight crews and aircraft proximity is summarized in Table 1.

TABLE 1. SMS Abbreviated Hazard Severity Classification

| | Hazard Severity Classification | | | | |
|---|---|---|---|---|---|
| Applies to | Minimal 5 | Minor 4 | Major 3 | Hazardous 2 | Catastrophic 1 |
| Flight Crew | Pilot is aware of traffic. Compliance greater than or equal to 66 percent | Aircraft is in close enough proximity to require specific action. Low risk Analysis Event* | In close enough proximity on a course of potential collision. Medium risk Analysis Event* | Near mid-air collision. Proximity of less than 152 meters (500 feet). | Mid-air collision |

The Risk Analysis Event (*) severity indicators used in the calculations are defined in the SMS manual and include aircraft proximity and rate of closure, as well as ATC (timely) mitigation and pilot (timely) mitigation. The definition of severity shown in Table 1 is mostly applicable to aircraft operating under air traffic control. However, it shows, in the risk analysis events, that both distance between the aircraft and closure rate are considered in the determination of severity.

The RTCA Special Committee SC-228 defines conflict severity using three components [1]:

1. Horizontal Proximity (tau MOD)
2. Horizontal Miss-Distance projection (HMD)
3. Vertical distance

These 3 components are combined using the norm operator defined as,

$$x \oplus y = \sqrt{x^2 + y^2 - x^2 y^2} \tag{5}$$

The severity is defined as a percentage with 0 percent being the least severe and 100 percent the most severe. For any time step $N$, the severity of loss of well clear (SLoWC) is given by,

$$SLoWC_N = \left(1 - RangePen_N \oplus HMDPen_N \oplus VertPen_N\right) \quad (6)$$

The severity of the encounter is the worst or highest severity for all the time steps ... *N-1, N, N+1, N+2…* A mapping between the SC-228 definition of severity and the SMS classification is given in Table 2 [11].

TABLE 2. SEVERITY MAPPING FROM SC-228 TO SMS

| SC-228 Severity Levels | SMS Severity Classification |
|---|---|
| 0%-17% | 5, Minimal |
| 17%-33% | 4, Minor |
| 33%-47% | 3, Major |
| 47%-94% | 2, Hazardous |
| 94%-100% | 1, Catastrophic |

### B. *Scenarios*

Three encounter scenarios are modeled in the simulation:

- Head-on
- Crossing 90 degrees
- Ownship overtaking

The aircraft are at co-altitude in the three scenarios. In the nominal case for each scenario, the trajectories lead to a collision. At the initiation of each simulation run, the ownship is positioned at random, left or right of the nominal position, at a maximum distance of 366 meters (1,200 feet). The random distribution is uniform. Figure 5 shows a visual representation of the initiation of the head-on scenario.


Fig 5. Initial conditions and distribution for head-on scenario

The parameters for the visual acquisition algorithm in the simulation are shown below. They represent an encounter between typical general aviation aircraft on a clear day with good visibility.

Visibility: 20 statute miles (32.2 km)

Aircraft speed: 120 knots both aircraft head-on, crossing

Aircraft speed: 140 knots and 100 knots, overtaking

Traffic aircraft: Piper PA28, four seat, single engine piston

Crew: Single pilot

## VI. SIMULATIONS RESULTS

The simulations were performed for the three scenarios described in the previous section for the following 5 conditions:

1. Unmitigated. No maneuver is performed by the crew to avoid the conflict. Aircraft continue on initial trajectories.
2. Visual unaided. Pilot is scanning the sky covering his/her entire field of view.
3. Visual aided. Pilot has an indication where the traffic is (10 o'clock, 3 miles). He/she concentrates the visual search on that area.
4. Assisted DAA, tau = 0 sec. Pilot receives alerting and guidance. Pilot (virtual) implements heading maneuver to avoid conflict. The DAA algorithm is configure with a tau of 0 seconds.
5. Assisted DAA, tau = 35 sec. Pilot receives alerting and guidance. Pilot (virtual) implements heading maneuver to avoid conflict. The DAA algorithm is configure with a tau of 35 seconds.

### A. *Simulation assumptions and performance parameters*

The following assumptions were employed on pilot and aircraft performance:

- The traffic aircraft does not maneuver to avoid the conflict
- For visual acquisition runs, the virtual pilot starts the evasive maneuver 1 second after visual acquisition
- Because most visual acquisition occurs after a well clear violation and close to the traffic aircraft, the ownship never maneuvers to cross in front of the traffic. It always maneuvers away from the traffic
- For Assistive DAA runs, the virtual pilot starts the evasive maneuver 5 seconds after conflict detection
- The virtual pilot will "favor" horizontal maneuvers and will maneuver with a 3 deg/sec turn rate which correspond to a standard rate of turn [12].
- Calculation of severity is done with a protected volume of 366 meters (1,200 feet) horizontally, 137 meters (450 feet) vertically, and tau = 35 seconds. Note that there are 2 sets of parameters: The parameters to configure the DAA algorithm and the parameters used to calculate the severity of the encounter.

### B. *Results*

Ten thousand runs were performed for each of the 3 scenarios and 5 conditions for a total of 150,000 runs. The combined results for all 30,000 conflict encounters (head-on, crossing, and overtaking) are shown in Table 3.

TABLE 3. COMBINED RESULTS FOR ALL CONFLICT ENCOUNTERS (HEAD-ON, CROSSING, AND OVERTAKING

| | Severity | | | | | |
|---|---|---|---|---|---|---|
| Condi-tion | No LoWC | 5 | 4 | 3 | 2 | 1 |
| Unmiti-gated | 0% | 12.79% | 13.20% | 15.64% | 51.65% | 6.71% |
| Visual unaided | 28.32% | 12.61% | 12.72% | 12.92% | 32.67% | 0.89% |
| Visual aided | 49.15% | 16.11% | 13.61% | 9.07% | 12.06% | 0% |
| Assistive DAA τ=0 | 90.36% | 9.64% | 0% | 0% | 0% | 0% |
| Assistive DAA τ=35 | 100% | 0% | 0% | 0% | 0% | 0% |

The unmitigated runs show the severity of the modeled encounter geometries if no evasive maneuvers are executed by the ownship crew. The results show that all encounters exhibit some loss of well clear (LoWC) while an estimated average of 6.71% are potential midair collisions (MACs) and over 50%, near mid-air collisions (NMACS). The mitigation effect of unaided see and avoid reduces MACs to a 1% and NMACs to 33%. Aided see and avoid eliminated MACs but 12% (an estimated 3600) of NMACs remained.

The incorporation of assistive DAA eliminated all NMACs and nearly all LoWC cases. It must be noted that the results shown for this simulation assumes that there are no system failures or data dropouts, and that the flight crew, after a delay, always follows the resolution guidance. System failures, loss of surveillance, and crew errors will reduce the effectiveness of the DAA system.

Table 4 shows the results for the head-on scenario for the 5 conditions.

TABLE 4. RESULTS OF HEAD-ON ENCOUNTERS

| | Severity | | | | | |
|---|---|---|---|---|---|---|
| Condi-tion | No LoWC | 5 | 4 | 3 | 2 | 1 |
| Unmiti-gated | 0% | 17.32% | 16.26% | 13.67% | 46.52% | 6.23% |
| Visual unaided | 0.15% | 19.15% | 17.43% | 14.29% | 46.66% | 2.32% |
| Visual aided | 1.62% | 28.23% | 22.52% | 16.89% | 30.74% | 0% |
| Assistive DAA τ=0 | 71.08% | 28.92% | 0% | 0% | 0% | 0% |
| Assistive DAA τ=35 | 100% | 0% | 0% | 0% | 0% | 0% |

The results show that when no action or maneuvering is taken to avoid the conflict (unmitigated), the initial trajectories lead to a potential collision in 6.23 per cent of the encounters. Unaided see and avoid provides approximately a factor of 3 reduction in potential collisions but still allows approximately 1 in 3 collisions when the trajectories are initially in a collision course. See and avoid, when the flight crew has the traffic pointed, reduces the potential collisions to zero (for 10,000 encounter runs of which 6.23 percent where on a potential collision course). There is also a reduction in near mid-air collisions.

When a detect and avoid (DAA) system is utilized with tau = 0, collisions, mid-air collision, and both Major, and Minor severity encounters are eliminated. Additionally, 28.9 per cent of encounters had Minimal severity and 71.1 remained well clear. A DAA system with tau set to 35 seconds results in no loss of well clear.

Table 5 shows the results for the 90 degrees crossing scenario.

TABLE 5. RESULTS OF 90 DEGREES CROSSING ENCOUNTERS

| | Severity | | | | | |
|---|---|---|---|---|---|---|
| Condi-tion | No LoWC | 5 | 4 | 3 | 2 | 1 |
| Unmiti-gated | 0% | 0% | 5.96% | 19.72% | 66.01% | 8.31% |
| Visual unaided | 7.56% | 5.30% | 15.00% | 21.50% | 50.29% | 0.35% |
| Visual aided | 45.84% | 20.11% | 18.30% | 10.32% | 5.43% | 0% |
| Assistive DAA τ=0 | 100% | 0% | 0% | 0% | 0% | 0% |
| Assistive DAA τ=35 | 100% | 0% | 0% | 0% | 0% | 0% |

The crossing scenario results show a reduction by a factor of approximately 24 in potential collision for the unaided see and avoid. For the aided see and avoid, potential collisions are eliminated and the near mid-air collisions are significantly reduced. This improvement in the see and avoid performance can be attributed to the larger area of the aircraft seen by the ownship in a crossing encounter and to the reduced closure rate.

Table 6 shows the results of the overtaking scenario. The overtaking scenario is the most benign of the three scenarios with collisions being avoided by unaided see and avoid and no loss of well clear for aided see and avoid. The slow closure rate of the scenario allows ample time for the flight crew to visually acquire the traffic and perform an avoidance maneuver.

TABLE 6. RESULTS OF OVERTAKING ENCOUNTERS

| | Severity | | | | | |
|---|---|---|---|---|---|---|
| Condition | No LoWC | 5 | 4 | 3 | 2 | 1 |
| Unmitigated | 0% | 21.06% | 17.39% | 13.54% | 42.43% | 5.58% |
| Visual unaided | 77.24% | 13.37% | 5.74% | 2.59% | 1.06% | 0% |
| Visual aided | 100% | 0% | 0% | 0% | 0% | 0% |
| Assistive DAA τ=0 | 100% | 0% | 0% | 0% | 0% | 0% |
| Assistive DAA τ=35 | 100% | 0% | 0% | 0% | 0% | 0% |

### C. *Time of visual acquisition before Closest Point of Approach*

In the simulation runs, the time at which the flight crew visually acquired the traffic aircraft was recorded. Figure 6 shows the distribution of visual acquisition time before CPA.

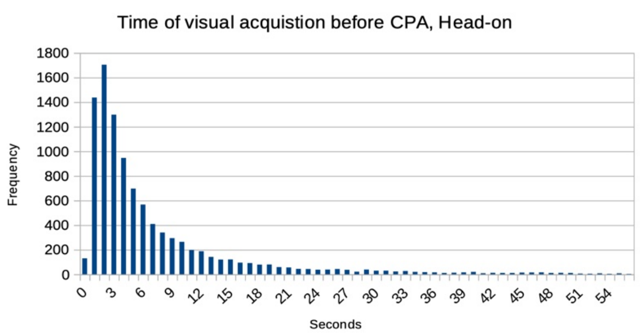


Fig 6. Time of unaided visual acquisition before CPA, head-on

The average and median time of visual acquisition before CPA is 6.89 seconds and 3.77 seconds, respectively, for the head-on unaided case. For acquisitions of 3 seconds or less before CPA, the flight crew has little or no opportunity to react and maneuver. More than 3 in 10 encounters result in acquisition of 3 seconds or less before CPA.

In the simulation, the virtual pilot reaction time for aided and unaided visual conditions was set to 1 second and it was assumed that evasive maneuvers, once executed, were successful in reducing the severity of the encounter.

Figure 7 shows the distribution of times for the 90 degrees crossing scenario.

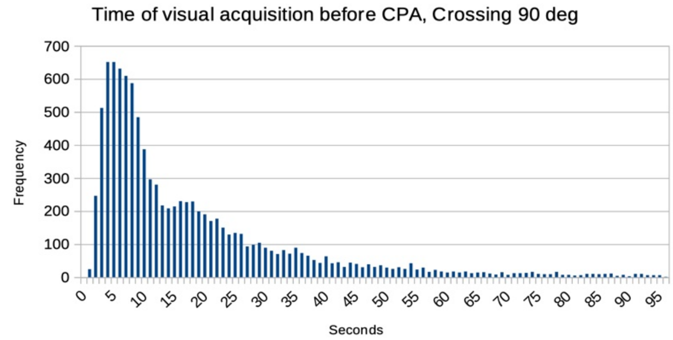


Fig 7. Time of unaided visual acquisition before CPA, crossing 90 degrees

The average and median time of visual acquisition before CPA is 17.13 seconds and 10.68 seconds, respectively, for the 90 degrees unaided case. As mentioned earlier, the visual acquisition model assumes that both aircraft in the encounter are level-flight and co-altitude. Different encounter geometries or assumptions would clearly affect the probability of crew visually acquiring traffic and also the time of visual acquisition before CPA.

## VII. SUMMARY AND CONCLUSIONS

Simulations were performed to assess the effectiveness of see and avoid with and without traffic advisories and how assistive detect and avoid technologies can improve the ability of flight crews to remain well clear of traffic aircraft in air encounters. Three different types of encounter geometries were modeled: head-on, 90 degrees crossing, and overtaking encounters. The probability of visually acquiring a traffic aircraft was calculated using a visual acquisition algorithm based on a validated model developed by MIT Lincoln Laboratory.

The simulation results show that for head-on encounters, unaided see and avoid provides a reduction of approximately a factor of 3 on the possibility of mid-air collision. For 90 degrees crossing encounters, unaided see and avoid reduces the possibility of mid-air collision by a factor of almost 24. When the flight crew is made aware of the location of the traffic aircraft by a traffic advisory or other means (aided see and avoid), the number of possible collisions were reduced to zero (for 10,000 runs) in the head-on and 90 degrees crossing scenarios. However, there were a large number of near mid-air collisions in both the aided and unaided see and avoid.

The assistive detect and avoid, where the flight crew is given alerting and guidance to avoid the conflict and remain well clear, eliminates all potential mid-air collisions, all near mid-air collisions, and all outcomes of severity Major and Minor. Most of the outcomes show no LoWC and only a small percentage of cases with Minimal severity remain.

These results strongly suggest that assistive detect and avoid could greatly enhance the capabilities of flight crews to avoid traffic and remain well clear.

The results shown in this paper were produced using a simulation and a virtual pilot which is deterministic and has a consistent behavior. Future work could include human in-the-loop experiments to measure and assess the behavior of humans in selecting resolution advisories, implementing the right-of-way rules as defined in the Code of Federal Regulations, ignoring alerts, implementing resolutions late, and/or making errors. The extension of the visual acquisition model for non-co-altitude aircraft encounters would enable studies of more complex geometries, representing more challenging see and avoid conditions for the crew.

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