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See and Avoid/Cockpit Visibility

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October 1989

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EXECUTIVE SUMMARY

This study was conducted in response to the Federal Aviation Administration's (FAA) Office of Aviation Safety and the recommendations of the Interagency Near Midair Collision (NMAC) Working Group, dated July 21, 1986, which suggested a review of See and Avoid effectiveness, conspicuity enhancement, and their relationship to cockpit visibility. This report summarizes the salient facts in these areas, based on a review of the literature, and assesses the potential for significant reduction of collision risk.

See and Avoid prevents the majority of collisions which would occur without it, particularly at low closing speeds. Traffic alerts to pilots improve on the probability of detection, but some collision threats are still not seen at all or in sufficient time to avoid a collision. The basic problem is that the detection performance of the human eye falls off rapidly with angular distance from the fovea, and the time required to scan for collision threats, even with target bearing information, may be short compared with the time the target is visible. Obstruction of vision by wings and engines during maneuvers and unfavorable sun position and windscreen conditions contribute to the problem. The cockpit visibility of transport aircraft is adequate to provide visual detection of general aviation aircraft which are collision threats. Cockpit visibility of general aviation aircraft does limit detection of transport and other general aviation aircraft which may be collision threats, but it is not clear that detection probability would be much improved if cockpit visibility envelopes were expanded because pilots might spend little time in searching at extreme angles. The cost/benefit of improved general aviation aircraft avionics, such as Mode C transponders, appears to be much better than that of structural changes to existing aircraft and, quite possibly, to increased visibility in new general aviation aircraft designs. The cockpit visibility of general aviation aircraft varies widely by make and model, and a systematic comparison might afford the public a better opportunity to include this factor in selecting aircraft. Comparisons of collision rates might reveal correlations with cockpit visibility accidents in student training, crop dusting, and other special operations would probably have to be eliminated in making such comparisons.

Terminal control areas (TCAs) provide a significant improvement over the basic level of safety achieved with See and Avoid alone, and the increased implementation and operational use of Mode C transponders should improve TCAs further. Terminal Radar Service Areas (TRSAs) have not provided a significant safety benefit to transport aircraft. Airport Radar Service Areas (ARSAs) should provide a significant benefit, but less than that of TCAs.

Automated conflict alert and collision avoidance systems are the next major step planned for the reduction of collision risk. There are significant problems to be solved. One is the compatibility of automated commands with pilot's preferences for avoidance maneuvers based on his experiences in Seeing and Avoiding other aircraft (reference 21). A second is that an automated system which provides protection against unforeseen maneuvers will generate alarms at aircraft separations permitted by air traffic control (ATC) unless the level of protection is compromised. A third is that the burden of avoidance generally falls on the instrument flight rules (IFR) aircraft which may disrupt ATC

operations by maneuvering on their own. A fourth is that general aviation aircraft, which may be only cooperating passively by providing transponder signals, may inadvertently maneuver so as to defeat escape maneuvers by heavy aircraft. A fifth problem concerns the tradeoff between the tolerable rate of alarms and the protection afforded by the system. Whether the net benefit of automated collision avoidance systems will be cost effective remains to be seen.

INTRODUCTION

It is clear from experience that pilots routinely visually detect and then avoid collisions with other aircraft, but occasionally two aircraft collide and they frequently miss by alarmingly small distances. These experiences remind us of collision risk and motivate continuing efforts to reduce it.

Since there are a great many ways of reducing collision risk, and each of them has different time, cost penalties, and safety benefits to the various users, there is an on-going controversy over the problem. If the costs and benefits of various approaches to reducing collision risk are accurately known, it is possible, in principle, to make regulatory decisions concerning the use of the airspace and the carriage of safety equipment based on cost/benefit reasoning.

Potential collision risk increases in proportion to the number of pairs of aircraft at risk (i.e., $N(N-1)/2$) or, approximately, as the square of the number of aircraft. Since other accident risks are directly proportional to traffic density, efforts to reduce collision risk below the level provided by See and Avoid alone intensify with increased traffic density.

As traffic increases near airports, standardized traffic patterns are developed and are used to establish regimented traffic flow. These patterns aid See and Avoid by reducing the relative velocity of encounters, by setting up encounters which may occur so that aircraft are in the field of view of each other, and by enabling pilots to focus visual search in directions in which other traffic is likely to appear. As the level of traffic increases, we find the use of Unicom to improve on the safety level provided by See and Avoid in the traffic pattern. At higher levels of traffic we find control towers without radar, and at still higher levels we have control towers with radar. As the traffic increases, the collision risk outside airport traffic areas produces an unacceptable risk and we have the introduction of voluntary radar advisory services (Terminal Radar Service Areas/TRSA), compulsory communications and limitation of traffic density (Airport Radar Service Areas/ARSA), and, at the highest traffic levels, we have the required carriage of Mode C transponder equipment, controlled entry, and minimum pilot certificate requirements in Terminal Control Areas (TCAs, Group I).

All of these measures to reduce collision risk have costs associated with them ranging from small flight diversions for proper traffic pattern entry to substantial equipment costs and circumnavigation of the airspace. All these measures, including the TCA, still rely to some extent on See and Avoid; controllers will depend on pilots who "have traffic in sight" to avoid collisions themselves. Since we rely on See and Avoid it is important to know how dependable it is under various circumstances.

HOW GOOD IS SEE AND AVOID.

Midair collisions are rare events. Near midair collision (NMAC) reports are relatively common. What is the meaning of this? Are there a vast number of potential collisions reduced to a large number of near collisions, and to a very small number of actual collision, by See and Avoid? Or is the small number of actual collisions due largely to chance? When See and Avoid fails, is it due to a failure by pilots to see other aircraft or to an inability to avoid them?

If two aircraft are on a collision or near-collision course and one or both crews see the other aircraft in time, they will routinely avoid each other and occurrence of the event will not be found in any data base. But if we want to estimate how effective See and Avoid is, we need an estimate of how many collisions or near-collisions would have occurred in the absence of pilot intervention. Estimates of these quantities are given in reference 1; we will summarize the findings here, discuss the degree of confidence in these estimates, and comment on the implications of this work for choices among measures to reduce collision risk.

We should distinguish between what is considered to be luck or to be skill in avoiding collisions. If two aircraft pass within 250 feet we assume that the pilots didn't have much time to avoid or success in avoidance, and that the pilots feel lucky that they didn't collide. If the encounter was between a high and a low performance aircraft, the collision cross-section is about 2580 square feet (using as an estimate the sum of the products of tail height of the first aircraft and the wingspan of the second aircraft and the tail height of the second aircraft and the wingspan of the first aircraft). If we assume that the miss distance is uniformly distributed over the 250-foot radius circle (196,500 square feet area), then there will be about one collision in 75 such encounters, on the average. If the encounter is between two low-performance aircraft, the expected ratio is one collision in about 260 such encounters. We can expect to get, as we do, a large number of frightening near midair collisions for every actual collision.

Table 1 summarizes the results of an analysis of the NMAC data of 1968-69 for four closing speed intervals, averaged over reports of all users (air carrier, general aviation, and military). These data are taken from reference 1 in which an estimate was made of the effectiveness of See and Avoid.

TABLE 1. EFFECTIVENESS OF SEE AND AVOID

<u>Closing Speed (knots)</u>	<u>Potential Conflicts (within 250 feet)</u>	<u>Actual Conflicts (within 250 feet)</u>	<u>Probability Detection</u>	<u>See and Avoid Effectiveness</u>
101-199	31,968	942	0.842	0.97
200-299	9,705	1,203	0.670	0.88
300-399	2,401	634	0.524	0.74
400+	948	501	0.320	0.47

The first column in table 1 divides encounters into four closing speed intervals. The second column gives estimates of the number of potential conflicts with miss distances within 250 feet; this is the estimated number of such conflicts in the absence of See and Avoid. The third column gives the estimated number of actual conflicts within 250 feet. These values are estimates rather than reported data because most NMAC are not reported, particularly at lower closing speeds. The fourth column gives the values of the probability of visual detection at 5 seconds from the point of closest approach. These values were derived from Howell's flight observations (reference 2). They show a significant probability that targets will not be seen, particularly at higher closing speeds. These detection probabilities have been substantially confirmed by three subsequent

flight tests (references 2-6), by theoretical work (reference 7) based on models of the eye's search characteristics, target size and contrast, and size of field to be searched, and again by tests run in a simulator using as stimuli slides taken in air-to-air near-collision runs (reference 8).

Figures 1 and 2 show the results of visual detection experiments run in a simulator using slides taken in air-to-air photography (reference 8). In figure 1, the cumulative probability of detection at 10 seconds from closest approach is plotted against the relative velocity in knots, showing the overriding importance of this factor. Results for a light aircraft (Musketeer) target are given with no pilot warning indicator (PWI) and with a high resolution (20°) PWI. In figure 2, the cumulative probability of detection of the Musketeer target is plotted against the time and range from closest approach in a run in which the relative velocity was 426 feet/sec. The maximum range at which the target was visible (which was determined by running the slides in time reversed order) was 23,480 feet (3.86 nautical mile). Very similar data can be found in reference 9 in a discussion of the Cerritos midair collision.

The fact that aircraft on collision courses may not be seen, although visible, led to substantial interest in providing traffic advisory (TA) services, and PWIs. The limitations of See and Avoid, even when supplemented by traffic information, led to interest in collision avoidance systems (CAS), which do not depend on visual acquisition of collision threats by pilots. TA, PWI, and CAS are discussed elsewhere in this report.

The effectiveness of See and Avoid depends on the probability of avoiding as well as on seeing, but the evidence available (reference 10), as analyzed in reference 1, shows that failure to See and Avoid is due almost entirely to the failure to see. Column 5 in table 1 gives estimates of the effectiveness of See and Avoid (See and Avoid Effectiveness) in preventing encounters within 250 feet; this is the number in column 3 of table 1 divided by the number in column 2. We see that, in the 101- to 199-knot closing speed interval, 97 percent of potential conflicts within 250 feet are avoided. Of those which are not avoided, we estimate that one in 75 to one in 260 results in an actual collision, depending on the size of the aircraft involved. At closing speed of over 400 knots, we estimate that only half the potential conflicts are avoided; escape from collision is primarily due to chance in these encounters.

We see from columns 2 and 3 in table 1 that the number of potential conflicts falls off rapidly with closing speed. This is attributable to the fact that most encounters involved either one or two low-speed aircraft, since two high-speed aircraft are almost always under air traffic control. It is also due to the organization of traffic flow for this very purpose.

In the estimates of table 1, encounters in overtaking geometries, in which only the crew of the overtaking aircraft can see the other aircraft, have been eliminated. These encounters contribute only a small fraction of those in the 101- to 199-knot speed interval. In an overtaking geometry, although only one crew can see the other aircraft, the probability of detection is relatively high, because the closing speed is low. The estimated effectiveness of See and Avoid is about 95 percent in the overtaking case in the 0- to 100-knot speed interval. A frequent cause of accidents between two general aviation aircraft on final approach is that when the closing speed is very low neither aircraft may be visible to the other crew. This subject is discussed in the section on Cockpit Visibility.

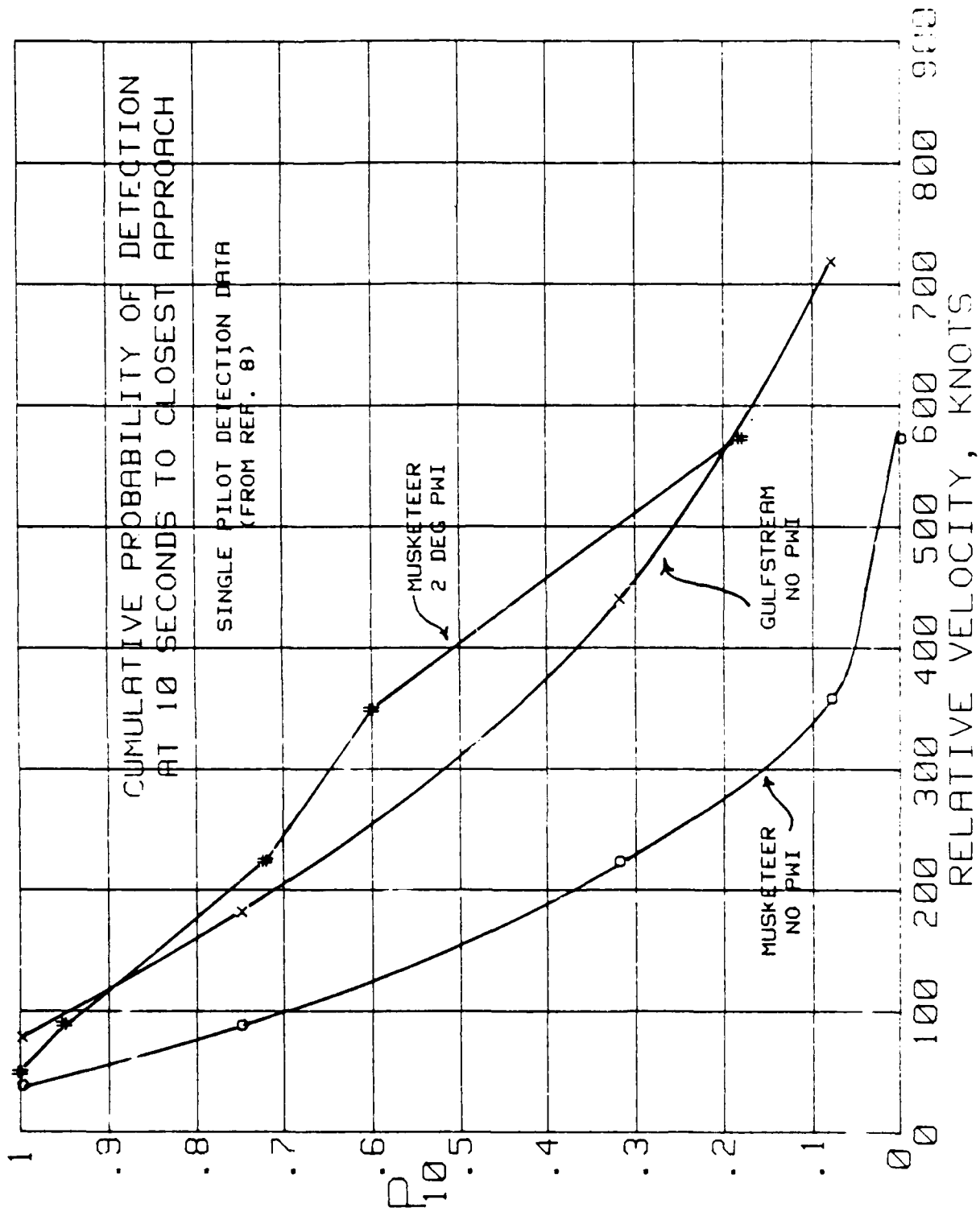


FIGURE 1. CUMULATIVE PROBABILITY OF DETECTION AT 10 SECONDS TO CLOSEST APPROACH

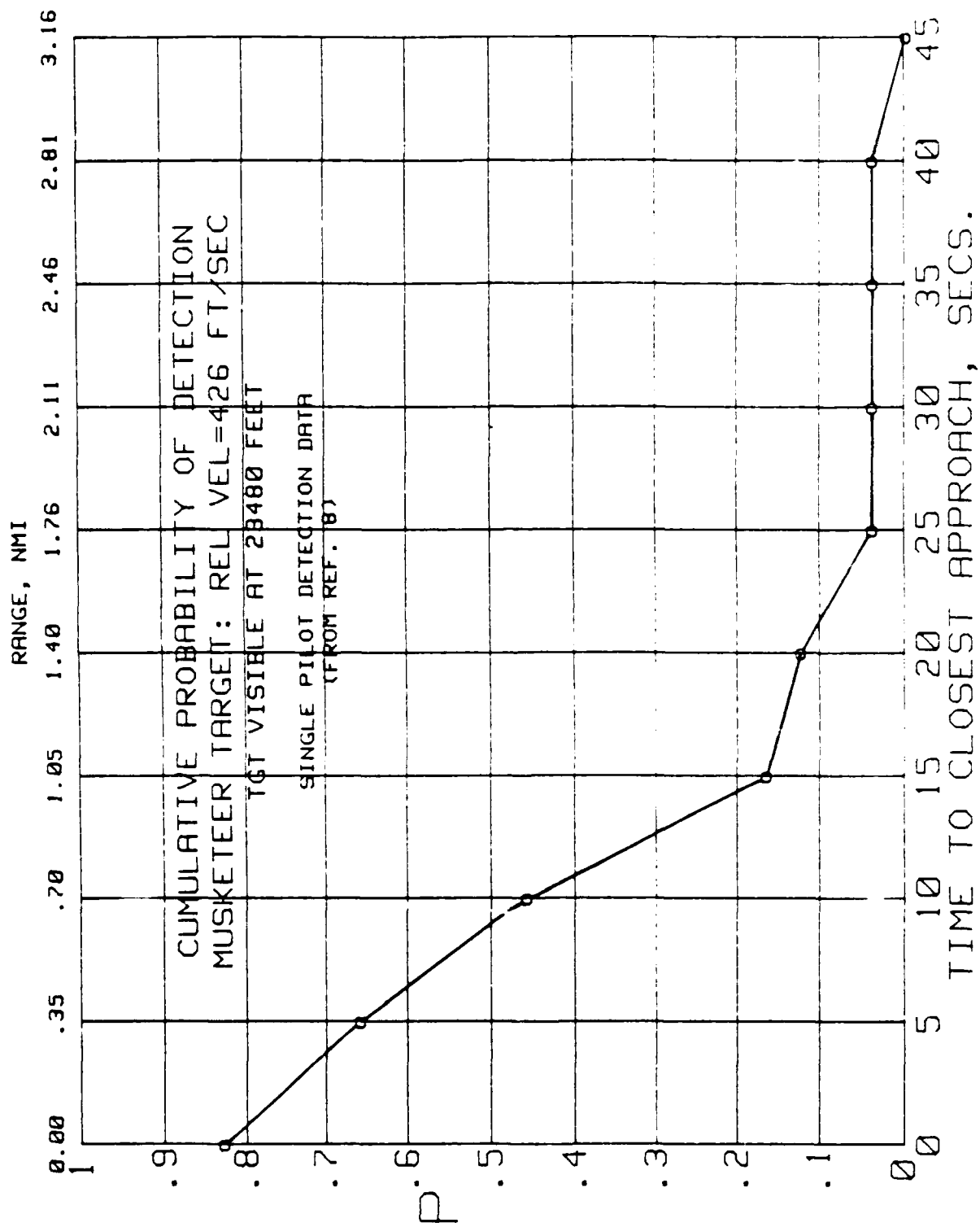


FIGURE 2. CUMULATIVE PROBABILITY OF DETECTION MUSKETEER TARGET:
RELATIVE VELOCITY = 426 FEET/SEC

Flight test data on target detection do not reflect the effect of the obstruction of vision by the wings of general aviation aircraft during maneuvers because all the tests have been run with aircraft in rectilinear flight, apart from corrections to flight path to achieve specified miss distances. Even though air carrier aircraft are relatively large targets, they are often unseen because of maneuvers, and NMAC reports include a high percentage in which one or both aircraft are maneuvering,

Other factors which should be borne in mind in interpreting See and Avoid effectiveness are the variability of pilot visual acuity and of air-to-air visibility, target size and aspect, target contrast, background complexity, crew workload and search patterns, and sun position. The answer to the question "How good is See and Avoid?" is "It depends on all these factors."

There are so many combinations of these factors that we do not have, and we can hardly hope to get, a quantitative measure under all the conditions which are experienced in the air. We do have air-to-air observations, under controlled conditions, of the probability of visual detection of aircraft of various speeds and sizes in various collision geometries. We have air-to-air tests of the probability of visual detection when the pilot is given traffic advisory information, and we have extensive simulation tests, using air-to-air photographic slides, of unaided and aided visual detection probabilities. We have results of simulation tests designed to measure the ability of pilots to avoid collisions.

This experimental work provides estimates of the effectiveness of See and Avoid under a sample of combinations of the factors which affect it. When these data are combined with information provided by NMAC reports, we can get an estimate of the effectiveness of See and Avoid as a function of closing speed and aircraft types, averaged over the various combinations of other factors as they occur in the airspace. The results given in table 1 are such an estimate.

We also have estimates of the effectiveness of See and Avoid in combination with various levels of air traffic control, including Instrument Flight Rules (IFR) versus IFR flights, IFR versus Visual Flight Rules (VFR), and VFR versus VFR in terminal control areas, terminal radar service areas, in the remaining hubs, and in the en route airspace. These results are discussed in the Beyond See and Avoid section.

This information can be useful in improving the effectiveness of See and Avoid, itself, and in providing a quantitative basis for cost/benefit analysis used in justifying compulsory ATC services, mandatory carriage of avionics, and segregation of the airspace. Even within TCAs, See and Avoid is relied upon for traffic separation between IFR/VFR and VFR/VFR flights for which the separation standards are less than for IFR/IFR flight pairs. See and Avoid is also a back-up to ATC in separating IFR from IFR flights, particularly on and near airports where speeds are low and aircraft are in close proximity. NMAC reports of IFR/IFR conflicts are evidence of "seeing" and frequently of "avoiding" collision threats caused by controller or pilot error.

The time from closest approach at which maneuvers are made and the choice of maneuver are important factors in the effectiveness of See and Avoid and in its interaction with ATC and with proposed automated separation services. The pilot must estimate whether or not a collision, or near collision, will occur in order

to avoid it. If he avoids by a horizontal maneuver, he will depend on his estimation of target range and bearing rate and of target attitude (to assess the effect of target maneuvers), and on the "rules of the road" to select the direction of turn. That is, he must be able to decide whether an imperceptible bearing rate is attributable to too great a target range to detect it or to an impending collision or near-collision. If he decides to turn he may elect to obey the rules of the road or, more likely, he will turn so as to keep his traffic in sight. He may estimate that there will be a miss too close for safety so that he elects to turn, but the sense of turn which keeps the target in sight may first reduce the estimated miss to zero, and then, he hopes, produce a larger miss of the opposite sense. In this event, he may climb or descend at the same time he turns. It appears that pilots do maneuver to keep their traffic in sight and depend on the other pilot, if the other pilot sees him, to make complementary maneuvers. The rules of the road do not consider these complications.

The estimation of vertical miss distance can be made, in principle, from elevation angle rates, but an altitude difference can be estimated at a greater range by reference to the position of the target with respect to the horizon. The horizon, however, may be poorly or erroneously defined, and estimates of relative altitude have been shown to be unreliable by air-to-air trials (reference 11).

We should bear in mind that greater displacements can be produced in a given time by turning than by climbing or descending. The International Civil Aviation Organization (ICAO) Rules of the Air specify turns for avoidance and state that aircraft shall avoid passing over or under the other, or crossing ahead of it, unless passing well clear.

The ranges and times to closest approach at which pilots are able to decide what maneuver to make and pilot preferences for maneuvers are important in considering the compatibility of pilot warning and collision avoidance systems with See and Avoid. Pilots exploit the high angular resolution of the eye to detect changes in bearing rates to estimate miss distances. These rates are not perceptible, in general, at IFR/IFR separation standards. Controllers use their superior information about aircraft position (from radar) and intentions (from communication) to predict relative position and thereby maintain separation.

Traffic advisories from controllers or alarms from PWI systems can be given at ranges compatible with the pilot's ability to See and Avoid other aircraft and appear to offer attractive approaches to reducing collision risk. But the TA and PWI approaches still leave a substantial collision risk and work shifted to Collision Avoidance Systems (CAS) which do not depend on collision assessment by the pilot. In the CAS, sponsored by the Air Transport Association (ATA), which used complementary climb/descent escape maneuvers, there was no target bearing information available; and it was thought necessary to instruct the crew not to assume that CAS commands were generated by traffic the crew could see.

THE HUMAN EYE

Since the failure to See and Avoid is primarily due to the failure to see, it is helpful to consider the detection performance of the eye and the problems of improving it by reducing the size of the field to be searched (by TA or PWI).

The ability of the eye to detect a target falls off rapidly with angle from the fovea. It is down by about 50 percent at 30 feet (half a degree) off the fovea (reference 12). And it takes about 0.3 seconds of fixation for the image to develop and the observer to detect the target. (It takes, then, about 540 seconds to search a 15° by 30° field in such a way as to achieve the maximum detection capability of the eye). It is, then, relatively rare for targets to be detected when they are first detectable because it is unlikely that the eye will be fixated within the narrow cone of maximum detection performance. Furthermore, pilots have other workloads and can only spend a fraction of their time in search for collision threats.

These facts are widely known and account for the usefulness in collision avoidance of traffic advisories and additional crew members, and led to an intense interest in PWI. Merely alerting a pilot to the presence of traffic within some range and altitude band would appear to be highly useful because the pilot can be expected to search full time for his traffic. But if he is unlikely to detect it in 10 or 15 seconds, he may have to interrupt his search to return to other tasks and fail to be looking at the time and in the direction when and where the target is visible. The expectation that a traffic alert, without bearing information, would have little utility was borne out by theoretical (reference 7) and experimental work (reference 8). But this same work produced the somewhat surprising finding that while moderate bearing accuracy (30°) produced a significant improvement in detection probability it still left a significant fraction of targets undetected. A simulated system with a 2° bearing accuracy showed a significant improvement over a 30°, but it still fell far short of the performance achievable with foveal detection of a fixated target.

The theoretical work reported in reference 7 in 1972 anticipated these findings. They estimated, for a head-on Cessna 180 target at a closing speed of 320 knots with the pilot alerted at 3 nautical miles, that a fixated target would be detected half the time at 23 seconds to closest approach. If the search field were confined to 15° by 60° the 50 percent detection point was 10 seconds; it improved only to 12 seconds if the field were reduced to 15° by 30° and only to 14 seconds if the field to be searched were further reduced to 15° by 15°.

AIRCRAFT CONSPICUITY

Extensive studies have been made, using both ground-to-air and air-to-air observations, of the importance of the color of paint, patterns, etc., which could be used on aircraft. Fluorescent and nonfluorescent paints and paint/pattern contributions to aircraft detection ranges and flight altitude estimation by observers have been studied (references 13 and 14). The conclusion reached was that there were no significant differences between threshold detection ranges for aircraft with fluorescent and those with nonfluorescent paint (reference 15).

These conclusions were reached with real aircraft targets subject to the loss of contrast which occurs with transmission through the atmosphere. Fluorescent colors are discernible at longer ranges than nonfluorescent colors, but color is not a significant factor in detection.

It should be noted that in 80 percent of first detections in the field trials reported in reference 13, the contrast was negative. In another 9 percent it was both positive and negative, in 8 percent it was positive, and in 3 percent detection occurred due to a specular reflection. Clearly, there is no obvious choice. An all black aircraft would be seen further, in principle, in the majority of cases when contrast is negative. But this might enhance detection very little while sacrificing detectability significantly for the less frequent positive contrast cases.

The judgment of attitude (measured by a weighted score including roll, pitch, and heading) does not vary much with paint pattern, although some pattern is slightly better than none at all. It is doubtful that heading and pitch are significant cues in collision avoidance, which depends on the estimation of range and that of bearing and elevation rates and on the detection of turns. One might expect that there would be an advantage in the detectability of turns in painting wing tops a light color (also more visible against the ground) and wing bottoms a dark color (also more visible against the sky). The data given in reference 14, in which such patterns were tested, do not report the roll detection results separately. It might be worthwhile to recover the raw data or, failing that, to rerun that part of the experiment.

The use of lights as aids to conspicuity, both by day and by night, have been extensively investigated (references 16 and 17). The NMAC Study of 1968 (reference 18) reported that "Aircraft colors or lights in use play no significant role in first directing a pilot's attention to the 'other' aircraft during daytime." A literature search reported in reference 17 also concludes that practical lights are not aids to daytime detection of aircraft.

The use of anticollision lights at night provides good conspicuity (reference 7). But the high probability of detection at night may be associated with a lower probability of avoidance. Tests of pilot's ability to avoid collisions were made in a simulator using projected images of an aircraft (reference 10). There are two reasons to suspect that the ability to avoid collisions at night may be poorer than these experiments suggest, because the horizon was well defined in the simulator used for the test, but it is often poorly defined at night in the air. Second, with multiple anticollision lights, the relative bearing to targets appears to dance about, and the apparent bearing appears to wander due to the autokinetic effect, so that the detection of bearing changes may be more difficult at night than in daytime encounters.

The relative infrequency of nighttime collisions cannot be readily attributed to more successful detection and avoidance. The lower density of traffic, the shorter hours of exposure, and the lower proportion of VFR flights, make the estimation of the relative potential collision risk at day and night difficult.

COCKPIT VISIBILITY

This discussion concerns the relationship between cockpit visibility standards and See and Avoid requirements. Visibility requirements are very sensitive to the assumed speed distributions of the aircraft in conflict. If the speeds of two aircraft are very different and they limit themselves to standard maneuvers, the slower aircraft will almost always appear well within current standards for

transport aircraft. The faster aircraft, on the other hand, can be outside of the visible field of the crew of the slower aircraft, most generally in overtaking geometries. Two aircraft at approximately the same speed can approach each other from any direction, in both elevation and azimuth, and no practical standard can assure the possibility of visual detection by at least one crewmember.

There appears to be a general reluctance to accept the fact that a significant fraction of general aviation aircraft on collision courses with air carriers will not be seen, even with traffic advisories. When there is a collision, there is an effort to "explain" it by finding that the target was not visible because of cockpit visibility limitations, or that the crew mistook another aircraft for the identified traffic. If the facts are, as they appear to be, that one in 20 to 80 collision encounters between air carrier and general aviation aircraft at terminal area airspeeds will result in a collision, even though the general aviation aircraft is always in the field of view of the crew of the transport aircraft and the transport aircraft is usually in the field of view of the general aviation aircraft, then this problem cannot be solved by improving the cockpit visibility of the air transport aircraft. One can only ask whether it is cost/beneficial to improve the cockpit visibility of the general aviation aircraft.

The risk to general aviation aircraft of fatal accidents from midair collisions is almost entirely from collision with other general aviation aircraft. But this risk is only about 3 percent of the total fatal accident risk to these aircraft so reducing collision risk has a very low priority in terms of investments in safety. The incentive to reduce collision risk comes from operational restrictions imposed on general aviation aircraft to reduce collision risk to air transport aircraft. Considering that pilots are unlikely to spend much time in searching at extreme azimuth angles, extending light aircraft cockpit visibility is unlikely to provide much reduction in collision risk with air carriers. The expense of such structural modifications to existing aircraft must be high compared with, for example, carrying Mode C transponders and radios. In other words, improved general aviation avionics is less expensive and more effective than improved cockpit visibility in reducing collision risk to air carriers. This argument is not so compelling for newly designed general aviation aircraft, but it is probably still valid.

There appears to be no systematic study of the effects of the conditions of windows on detection probabilities. But it is common experience that the effects of oil films, dirt, crazing, and pitting, combined with unfavorable sun position, can make visual detection next to impossible.

The current cockpit FAA visibility standard for transport category aircraft Federal Aviation Regulation (FAR 25.773) and Advisory Circular AC29-773-1 (reference 19) cites the Aerospace Standard AS 580B of the Society of Automotive Engineers (SAE) (reference 20) as "acceptable means of compliance." This standard resulted from a computerized study of ten million hypothetical cases of pairs of aircraft on collision courses, "considering reasonable mixes of types, speeds, flight path angles, etc." as well as "...all known available data from actual midair collisions, reported near misses and ATC called hazardous traffic..." A similar computer study was done for the restricted set of encounters between air carriers and general aviation aircraft (reference 3); it showed that the SAE standard was adequate for these encounters. While situations can be imagined in which two air carrier aircraft could collide

without either crew seeing the other because of cockpit visibility limitations, encounters of which this is true represent a very small percentage of near midair incidents and no IFR/IFR collisions involving air carriers. One such hypothetical situation is a controller or pilot error resulting in a climb or descent through the altitude of another aircraft on the same airway moving at nearly the same speed. Errors of this kind are rare, and they are likely to be detected by conflict alert systems in the en route airspace.

Although the cockpit visibility of general aviation aircraft is not regulated by an Advisory Circular specifying an "acceptable means of compliance," the FAA has conducted a flight test program to estimate the minimum requirements in various phases of flight (reference 20) and has made extensive surveys of the visibility from many makes and models of aircraft (reference 21). But this information has not been consolidated in a form which permits a ready comparison useful to the public. The wide variation in cockpit visibility suggests that manufacturers have very different ideas of the optimum tradeoffs between the conflicting design factors, including cost. There are, of course, different designs based on different needs, which vary with the typical use of the aircraft.

BEYOND SEE AND AVOID

The occurrence of midair collisions in VFR conditions has resulted in never ending efforts to prevent them ranging from early efforts at traffic separation, based on manual flight following, to recent efforts at the development of automated collision avoidance systems (CAS). Almost every attempt at reducing collision risk relies on See and Avoid as primary protection. Radar advisory services which attempt to improve the probability of detection (and sometimes of avoidance when the intentions of the other pilot are given). Secondary protection occurs when controllers permit closer proximity than IFR permit when pilots "have traffic in sight," or when pilots intervene in emergencies created by their own or controller errors.

There are a great many combinations of levels of air traffic control, airspace restrictions, and avionics requirements to be found in use. And there is a continuing debate over the most cost/effective ways of reducing collision risk, with the air transport industry generally favoring less reliance on See and Avoid, and the general aviation aircraft operators favoring as much, or more.

An extensive study was made, using NMAC reports provided by the National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System, of the relative protection against collision provided in various segments of the airspace, taking into account the variations in potential collision risk associated with the different traffic levels and user mix in each element of the airspace analyzed (reference 22). This work showed how much of the collision risk for each user is to be found in the various segments of the airspace, such as TCAs, TRSAs, other hubs, and en route airspace, and how this risk is divided within these segments. For example, it was found, in the 1976-78 time period of the study, that 44.9 percent of the collision risk to air carrier aircraft still occurred within TCA hubs (defined as a cylinder of a 30-nautical mile radius and 12,500-foot height) and that a little more than half of this risk occurred within the boundaries of the TCA proper (24.6 percent). Of the risk within the TCA boundaries about 40 percent was within 5 miles and 3,000 feet above ground level (AGL) of towered airports.

This analysis showed that TCAs improve protection of air carriers from general aviation aircraft by a factor of 2.3 to 3.2: How much of the improvement is attributable to increased control and how much to avoidance of the TCA airspace by light aircraft could not be estimated by the analysis. The predominant difficulties reported by air carrier pilots were those of general aviation aircraft illegally within the TCA proper and overloaded and/or undercoordinated controllers (particularly where two IFR aircraft were in conflict).

The analysis of these NMAC reports showed that about one-third of the risk to air carriers was found in the 79 TRSA hubs in operation at that time. The TRSAs appeared to provide little safety benefit to air carrier and military aircraft but some reduction in risk of collision between two general aviation aircraft. Of the TRSA air carrier risk about two-thirds occurred within the TRSA proper; of this, about one-third was within air traffic areas (ATAs) but outside the immediate vicinity of the airport (the conflicts were above 250 feet AGL). A little more than one-half of the risk within TRSA proper was outside ATAs. Based on the distribution of NMACs in TCAs, the conversion of TRSAs to ARSAs will result in a substantial reduction in the risk to air carriers in the outer part of ATAs and a small reduction within ARSAs outside ATAs.

The next significant reduction in collision risk is expected to come from automated conflict alert and collision avoidance systems. Systems of this kind have been under development for a long time because they are trying to solve a difficult problem, which is, that the controller who knows where aircraft will be (because he is telling them or being told) can permit closer traffic spacing than a system which only knows where aircraft will be if they do not accelerate in any direction. The automated systems must generate alarms under conditions which are safe when intent is known, or the automated systems must be designed to tolerate separations which might be dangerous. If it turns out that alarms generated under safe conditions can create hazardous situations when they conflict with ATC, then the automated systems will have to be designed with reduced alarm volumes compatible with ATC separations. Or, perhaps, these systems will only be used in parts of the airspace where ATC is not providing separation between IFR and VFR aircraft. What the safety benefit will eventually turn out to be is unclear, so the cost/benefit justification of these systems present a thorny problem.

CONCLUSIONS

In general, the above study and appendix A have surfaced a number of key points in See and Avoid and its relationship to cockpit visibility:

1. The effectiveness of See and Avoid depends on the probability of avoiding as well as on seeing, but the evidence available shows that failure to See and Avoid is due almost entirely to the failure to see (in daytime).
2. See and Avoid prevents the majority of collisions which would occur without it, particularly at low closing speeds.
3. At high closing speeds, escape from collision is primarily due to chance as the detection probability of one or both aircraft is very low.
4. See and Avoid is a backup to air traffic control in separating aircraft, particularly on or near airports where speeds are low and aircraft are in close proximity.

5. The importance of the color and type of paint used on aircraft indicates that color is not a significant factor in detection of other aircraft.

6. The effect of paint patterns on the ability of observers to estimate aircraft altitude indicates that some pattern is slightly better than none at all.

7. Aircraft colors or lights in use play no significant role in first directing a pilot's attention to the other aircraft during daytime.

8. The use of anticollision lights at night provides good conspicuity and, therefore, a high probability of detection. The ability to avoid aircraft at night, with various lighting arrangements, has not adequately been studied.

9. Based on the facts, that collision encounters between air carrier and general aviation aircraft at terminal area airspeeds will result in a collision, even though the general aviation aircraft is always in the field of view of the crew of the transport aircraft and the transport aircraft is usually in the field of view of the general aviation aircraft, then this problem cannot be solved by improving the cockpit visibility of the transport aircraft.

10. The risk to general aviation aircraft of fatal accidents from midair collisions is almost entirely from collision with other general aviation aircraft.

11. Pilots are unlikely to spend much time in searching extreme azimuth angles, therefore extending general aviation aircraft cockpit visibility is unlikely to provide much reduction in collision risk with air carriers.

12. The cost/benefits of structural modifications to enhance the cockpit visibility envelopes of existing aircraft must be compared with improved avionics (i.e., Mode C transponders, communications, etc.) which may be less expensive and more effective than improved cockpit visibility in reducing risk to air carriers.

13. The effects of cockpit windscreen pitting, crazing, films, dirt, bugs, sun position, etc., on detection probabilities may be significant.

14. Wide variation in cockpit visibility envelopes suggests that general aviation manufacturers' have different ideas of the optimum tradeoffs between aircraft design factors, different needs, and flight safety.

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APPENDIX A

ANALYSIS OF STUDY AND CONCLUSIONS

Analysis of the Near Midair Collision Data

An analysis was conducted using the Near Midair Collision (NMAC) data of 1968 to 1969 for four closing speed intervals, averaged over reports of all users (air carrier, general aviation, and military). With the data, when combined with numerous experimental flight tests and cockpit simulations data, an estimate of the effectiveness of See and Avoid was developed. (These air-to-air experiments did validate the initial analysis).

It may be useful to revisit the past analysis and current NASA Aviation Safety Analysis System data (i.e., NMAC predecessor) in order to compare/validate the results. There are a number of questions, though, which should be considered; i.e., Can it be done? (The two data bases have changed over the years and may not be comparable.) Is it worth doing? (It may be a laborious and expensive process to extract the data and compare.) What are we going to learn from it that we do not already know?

See and Avoid

1. Much work has been accomplished in simulation, flight tests, and NMAC analyses with single pilot/observer time/range of detection of intruding aircraft. One question that remains is the improvement in probability of detection of an intruding aircraft with multiple crewmembers (i.e., pilot and copilot). Therefore, one may suggest the need to compare time/range of detection of two observers (versus one observer) in the same cockpit.

The assumption that the probability of detection of multiple observers is simply related to that of a single observer could be verified. That assumption, that the observers (multiple) detect independently with the same probability of detection per unit of time, is an oversimplification (because the field of view is different for each observer). Another assumption implicit in finding the combined average probability of detection by that simple model is that the intrinsic probability of detection is constant from run to run; this is not true.

This experiment could be conducted in a controlled flight test by having multiple crewmembers (pilot and copilot) signal to a recorder (hidden from opposite observer) each pilot's time/range of detection. Data could be analyzed, combined, and singularized for the time/range of detection.

2. In review of the literature, it is not known whether the relationship of See and Avoid to the current Traffic Alert and Collision Avoidance System (TCAS) development has been adequately studied. If not, a study of compatibility of TCAS commands with pilot judgement based on See and Avoid should be conducted. There may be a major conflict of TCAS commands versus how the pilot would elect to maneuver when he sees an intruder. A conflict of this nature could be serious, especially in the air traffic control environment.

Conspicuity Enhancement

1. The studies of paint and paint patterns on aircraft conspicuity have shown no effect on aircraft detection ranges and small effects on the pilot's ability to estimate a combination of roll, pitch, and relative heading. That is, the published report gives estimates of the pilot's ability to detect a combination of these variables. It is possible that the ability to estimate roll is significantly enhanced by painting wing top surfaces a light color and wing bottom surfaces a dark color. But this cannot be determined from the published report of this research, although this would be discoverable from the original data, if available. An effort to recover these data would be useful. In view of the importance of estimating whether targets are turning towards or away from an aircraft, a repetition of this work might be worthwhile if the details of the previous study are unavailable.

2. Pilots' ability to assess collision risk at night has been estimated to some degree in simulation. These are two situations where more data may be useful: (1) to estimate the relative bearing rate of an intruder aircraft (with current anti-collision lights, tell-tail lights, landing lights, etc.); (2) to estimate the relative altitude (above, below, same) of other aircraft in flight, to sample conditions in which the horizon is well and poorly defined.

Cockpit Visibility

1. This task as suggested is a comparison of individual cockpit visibility survey envelopes (per FAA/Barile report) by general aviation aircraft make and model. This would compare manufacturers' cockpit visibility envelopes (and each other) and compare typical general aviation configurations, size of windshield envelopes, etc. Then a review of collision history of these general aviation aircraft by make and model, type of operation, etc., could be conducted. (The latter task would be extremely difficult and laborious.)

From this comparison, specifically in general aviation, possible minimum guidance material or acceptable levels of compliance should be developed.

2. As related to the windshield, two tasks appear needed which could provide data for guidance material (as appropriate):

. A survey of typical operational aircraft windshields for transmissivity (inside out) due to states of cleanliness, pitting, films, particles, roughness, insects, etc. In conjunction with these measurement efforts, study the physical condition of the windshield as related to its optical properties (i.e., reflectivity versus scattering).

. Taking various above extreme examples (excellent to bad) of windshield states, conduct a ground test of approach to landing and departing aircraft (e.g., Washington National) with pilot observers sitting in sample aircraft for range of detection with various visibilities, ceilings, sun positions, etc., to determine the effects (on visual detection) of the windshield. Using the same pilots, external to the aircraft without windshield separation, acquire similar data.

These two efforts may suggest that windshield conditions in various visibilities, ceilings, sun positions, etc., inhibit timely detection of intruding aircraft and subsequently preclude effective avoidance maneuvers.