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Evaluation of Collision Avoidance Maneuvers for Parallel Approach

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Two candidate evasion maneuvers were evaluated for use with a collision alerting system for independent closely spaced parallel approaches in instrument conditions. The two maneuvers were a wings-level climb and a climbing turn away from parallel traffic. Pairs of aircraft on parallel approach were simulated by use of prerecorded trajectories covering a range of normal approach and blunder examples. Each example was repeated twice, with the endangered aircraft responding to alerts with either the climb-only or the climbing-turn evasion. The climb-only maneuver is shown to result in 38-times as many collisions as the climbing-turn for nominal alert threshold settings. It is possible to reduce the collision rate by adjusting threshold parameters, but the false alarm rate increases. The climb-only maneuver is shown to be uniformly less safe than the climbing turn for all parameter combinations. Results are illustrated with system operating characteristic curves.

Introduction

As part of the NASA Airborne Information for Lateral Spacing (AILS) program, a cockpit-based alerting system is required for aircraft on independent instrument approaches to closely spaced parallel runways.[1] The alerting system is designed to prevent collisions in the event that an aircraft blunders from its expected approach path. The current design goal is to enable approaches down to 2500-ft runway spacings, which is well below the current 4300-ft minimum (3400 ft at airports with the Precision Runway Monitor system).[2,3]

The NASA Langley Research Center has developed (and continues to study and modify) a candidate alerting logic for the AILS program.[1,4–6] As originally conceived, the system (also called AILS) commands evading pilots to perform a climbing-turn escape maneuver, combining vertical acceleration with a 45-deg track angle change away from the approach centerline. Simulations based on this evasion have shown AILS to improve safety for a variety of blunders at runway spacings down to 1700 ft.

For operational simplicity and to reduce training costs, a straight-ahead climb (termed here climb only) has been advanced as a possible substitute for the climbing turn. First, such a maneuver is compatible with current missed approach procedures and with the emergency maneuvers for existing alerting systems such as the Traffic Alert and Collision Avoidance System (TCAS) and Ground Proximity Warning System (GPWS).[7,8] To include a turn as part of a procedural avoidance maneuver would require additional pilot training and expense to airlines. Second, an aircraft turning off of the final approach course is more likely to interfere with other aircraft in the airport vicinity than one performing a straight-ahead climb, depending on the arrival and the departure routes of the airport. In selecting the climbing-turn evasion for AILS, it has been assumed that third-aircraft collisions during evasion maneuvers will be prevented by adequate design of traffic management procedures. This may include an effort to integrate TCAS with AILS so that alerts from each are coordinated, and one compensates for the deficiencies of the other. The goal is not necessarily to provide fully automated resolution of encounters, but to design the overall system so that air traffic controllers are guaranteed adequate time and space to intervene successfully. Use of a climb-only evasion maneuver instead of a climbing turn could simplify the design process.

Although desirable for the above reasons, the climb-only maneuver has performance limitations that make it a questionable substitution. The acceleration of an evading host relative to an intruder may be smaller in magnitude and duration with the climb-only than with the climbing-turn maneuver. This might result in either a reduced rate of success in avoiding imminent collisions or an increased rate of false alarms if alerts are made to occur earlier in an attempt to compensate for the relative gentleness of the maneuver. Analysis was needed to determine the feasibility of using a climb-only maneuver. In past research, a methodology was developed for evaluating the performance of alerting systems in terms of the collision rate and unnecessary alert rate for a specified set of trajectories.[6,9] The methodology was previously applied to AILS with the climbing-turn maneuver. That analysis has now been expanded to compare the two candidate evasion maneuvers, testing over a range of threshold settings so that the relative performance potential can be observed. The method and the results are the subject of this paper.

Airborne Information for Lateral Spacing Alerting Algorithm

The discussion here focuses on the version of AILS that had been developed as of January 1998. Because AILS is continuously being improved by researchers at NASA and Honeywell, the details of the algorithm may have changed since this analysis was performed.

AILS is envisioned as an airborne alerting system similar to TCAS, but specialized for the parallel approach environment. A computer on board each aircraft collects information from sensors and over datalink from neighboring aircraft. Using this information, the computer decides whether or not to issue an alert based on a worst-case assumption of possible aircraft behavior.

AILS displays alerts of several levels of urgency on one or both aircraft performing the parallel approach, depending on the nature of the conflict. However, the underlying philosophy is that adequate separation should be ensured even if a blundering aircraft is not responsive to alerts (e.g., because of some mechanical failure).

The full dynamic model used by AILS is too complex to describe here in detail, but the relevant parameters for this analysis are illustrated in Fig. 1. In Fig. 1, an encounter situation is shown from the point of view of a normally approaching host aircraft (on the left). The host is modeled as maintaining a constant-velocity approach along the extended runway centerline and glide slope. The intruder aircraft is modeled as potentially following any of a range of trajectories. The model trajectories include a circular path based on the turn rate measured by means of datalink and also a series of cases in which the intruder rolls out into straight-line flight. The result is a fan of potential trajectories, as shown. The intruder's airspeed and vertical velocity are assumed to be constant at all times.

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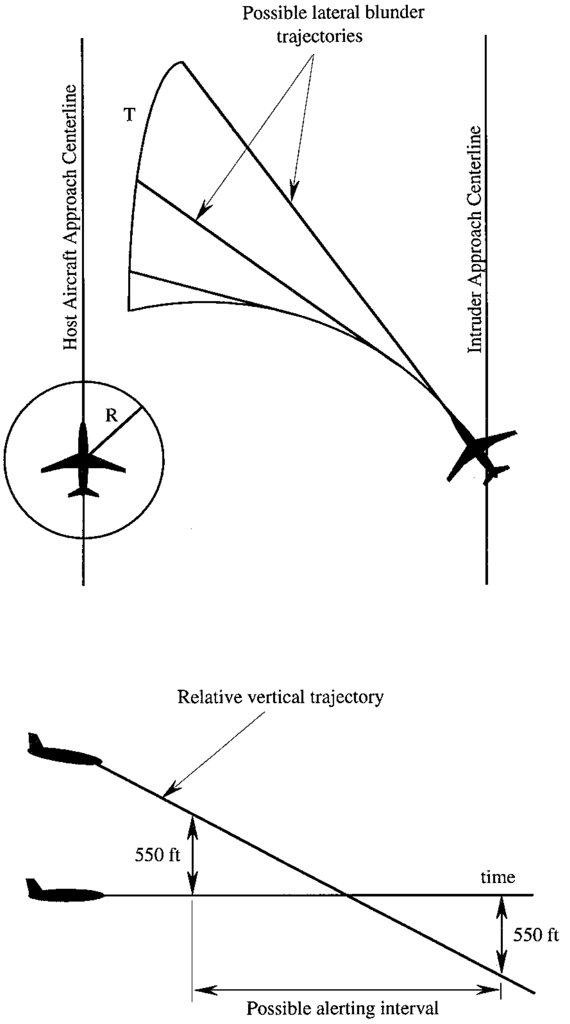


Fig. 1 AILS lateral and vertical geometry.

Two parameters, called R and T, are used to define the alerting threshold. If it is possible for the intruder to pass within R horizontal and 550 vertical feet of the host in under T seconds, an alert is issued to the host. Although the true AILS logic is able to generate a sequence of alerts (each based on a different combination of R and T) of increasing criticality as the intruder closes in, this research focuses on the final breakout alert.

Acceptable values of R and T were determined for several runway spacings by NASA through a trial-and-error process of blunder simulation. In these simulations, the host aircraft performed a climbing-turn escape maneuver in response to breakout alerts. For the 2500-ft runway spacing, the values used in simulation tests have been $R = 550$ ft and $T = 13$ s. These values are referred to as the nominal parameter values in the remainder of this paper.

System performance was expected to degrade if the nominal R and T values were used with the climb-only maneuver in place of the original climbing turn. This is because the climbing turn generally provides additional separation between aircraft that is due to the turning component. Thus the time available in which to escape is different with each type of maneuver, resulting in different optimal values for R and T. The analysis discussed here was designed to determine whether adequate performance is obtainable with the climb-only evasion through adjustment of R and T only or whether a more complete redesign of the alerting algorithm would be required.

Approach

Alerting logic performance was estimated with a numerical trajectory simulation developed previously.[5,6] Intruder trajectories were based on a prerecorded trajectory set provided by Rockwell-Collins.[4] These were sampled at approximately 2 Hz from piloted flight on a Fokker 70 simulator and cover a range of behavior: normal approaches; slow constant-rate turns at a 5-deg bank angle; coordinated heading changes of 5, 15, and 30 deg; and two types of fake blunder, in which the intruder aircraft begins a blunder but returns to its proper approach path before crossing that of the threatened aircraft. Separate trajectory data were recorded for calm and turbulent conditions and for airspeeds of 130, 145, and 160 kn. To expand the variety of possible encounters further, this set of trajectories was used over a series of initial longitudinal separations (within ±1.5 n mile of the threatened aircraft), initial vertical separations (within ±1000 ft), and vertical speeds (ranging from descent along the glide slope to a 2000-ft/min climb). Lateral spacings were set to a 2500-ft runway spacing. In total there were 36,270 trajectories used in the simulations.

Pairs of aircraft were simulated in fast time, one performing an ideal normal approach while another (the intruder) followed each of the prerecorded blunder or normal approach paths from the above-mentioned set. The alerting logic was implemented for only the threatened aircraft (the host) to simulate a case in which the blunderer is unable to respond to alerts. Note that this two-aircraft simulation does not account for the possibility of a three-aircraft incident, which is assumed to have been precluded through airspace and procedure design.

In separate simulation runs, the host aircraft responded to alerts with either the climb-only or the climbing-turn avoidance maneuver. The climb-only avoidance maneuver consisted of a 2-s response delay, followed by a 0.25-g pull-up to a 2000-ft/min climb rate, and a 15-kn airspeed increase at 1 kn/s acceleration. The climbing turn added to this a 15-deg/s roll (following the delay) to a 30-deg bank angle, with roll-out at a track angle 45 deg from the approach centerline.

The 2-s response delay is shorter than the 5-s delay assumed for the existing GPWS and TCAS alerting systems. Use of the former number with AILS originated with NASA Langley researchers, who have suggested that a rigorous pilot training program, and the fact that the final approach is a brief interval during which concentration can be maintained, may make short reaction times possible.[1] A 2-s reaction time assumption is already standard in some cases, for example with engine fire alerting systems.

Note that the above evasion procedure was designed to be performed open loop by pilots—that is, with no guidance by the alerting system after the initial alert. This differs from an alerting system such as TCAS, which actively guides pilots in performance of evasion maneuvers and continuously updates maneuver goals, depending on whether separation is being achieved. With AILS, the assumption is that a trained open-loop maneuver will allow a shorter reaction time and be performed more consistently than a guided maneuver.

The outcome of each approach was recorded, including 1) whether an alert was generated, 2) whether a collision occurred, and 3) whether an alert was really necessary. Six mutually exclusive categories, listed in Table 1, were used to classify the possible outcomes. A collision was defined to have occurred if separation at any point during an approach was less than 500 ft. An alert was considered necessary if a collision would have occurred without an alert. Thus an alert in a case in which a 501-ft separation would have occurred without the alert is by definition unnecessary. Such a definition is required as a specific performance metric, even though violations of the 500-ft limit do not guarantee collisions in reality, and separations over 500 ft might intuitively merit prevention. A pilot or controller's impression of "necessary" is important, but is subjective and difficult to use analytically.

If an alert was not issued at all during an approach, the run was classified in Table 1 as either a correct rejection (if a collision did

Table 1 Outcome categories

Outcome category	Alert issued?	Collision occurred?	Alert necessary?
Correct rejection	No	No	No
Missed detection	No	Yes	Yes
Unnecessary alert	Yes	No	No
Induced collision	Yes	Yes	No
Correct detection	Yes	No	Yes
Late alert	Yes	Yes	Yes

Table 2 AILS performance summary[a]

Maneuver	Correct rejections (CR)	Missed detections (MD)	Unnecessary alerts (UA)	Induced collisions (IC)	Correct detections (CD)	Late alerts (LA)
Climbing turn	0.98227	0	0.01257	0.00008	0.00505	0.00003
Climb only	0.98227	0	0.00948	0.00317	0.00403	0.00105

[a] 36,270 simulations; nominal threshold parameter values; 2500-ft runway spacing; 2-s pilot reaction time.

not occur) or a missed detection (if a collision did occur). If an alert was issued, the outcome was placed in one of four categories. An unnecessary alert was a case in which an alert was not required for preventing a collision, but was issued anyway, and no collision occurred. If an alert triggered a collision when none would have occurred otherwise, the run was classified as an induced collision. A correct detection occurred when a collision was averted because of an alert. Finally, a late alert was a case in which an alert was issued too late to prevent a collision.

To see the dependence of performance on the threshold parameters, separate simulations were performed over a range of R and T values. For this, R was varied from 350 to 750 ft in 100-ft increments, and T was varied from 5 to 25 s in 2-s increments. To examine the sensitivity of performance to pilot reaction time, a second series of simulations varied reaction time from 0 to 15 s in 1-s increments, with R and T fixed at their nominal values of 550 ft and 13 s, respectively.

Results

The quantities of actual interest in alerting performance are the rates of collision and false alarm. In terms of the categories of Table 1, collisions are the union of missed detections, induced collisions, and late alerts. False alarms include both unnecessary alerts and induced collisions. Because of the uncertainties in aircraft trajectories, reducing the collision rate by increasing R or T will result in an increase in the unnecessary alert rate. Because false alarms have deleterious effects of their own on long-term safety (by degrading pilot confidence in the system), choosing thresholds requires a conscious tradeoff between collisions and false alarms to attain the best system performance.

The primary question, then, is whether adequate alerting performance is possible with the climb-only evasion maneuver with some combination of R and T. At least a partial answer to this question is obtained when performance metrics are plotted as functions of system parameters by simulation output, as is discussed below.

Performance Summary

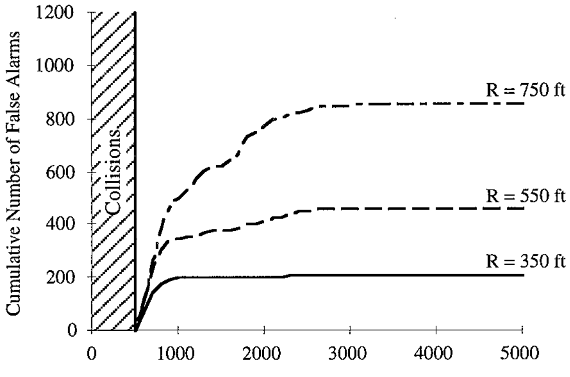
Table 2 shows a comparison of observed outcome rates between the climbing-turn and the climb-only escape maneuvers. These results are for $R = 550$ ft and $T = 13$ s. When climb-only maneuvers are substituted for climbing turns, there is an approximate 40-time increase in the rate of induced collisions, along with a 35-time increase in late alerts. This is an overall 38-time increase in collisions.

False Alarm Analysis

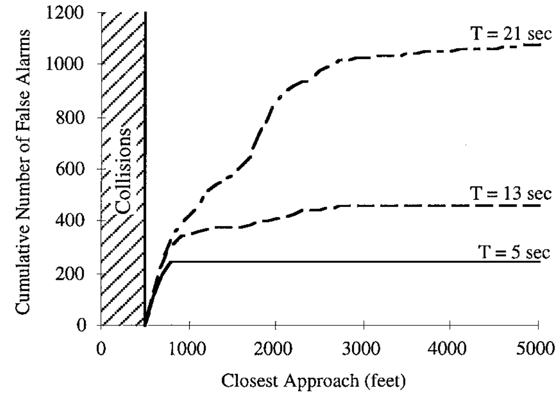
Figure 2 summarizes false alarm performance over a range of R and T values. Curves relate the cumulative number of false alarms to the closest approach of the two aircraft had no alert been issued. For example, if the cumulative number of false alarms equals 400 at a closest approach value of 2000 ft, then 400 of all false alarms that occurred were such that a closest approach below 2000 ft would have occurred had there been no alert.

Figure 2a shows data for a constant T of 13 s and three values of R, and Fig. 2b shows data for $R = 550$ ft and three values of T. Increasing the value of either T or R results in a greater number of false alarms at every closest approach distance. The variable slopes of the curves in the plots are due to characteristics of the specific blunder trajectories that were used.

It is useful to distinguish between two types of false alarms: those that occur during actual blunder cases and those occurring with the intruder on a technically correct approach. The first type of false alarm is of limited importance in system design in view of the fact that blunders are extremely rare events. Frequent false alarms that disrupt normal approaches, on the other hand, would tend to reduce pilot confidence in the validity of alerts and would have a negative impact on traffic flow.



a) Varying R with T = 13 s



b) Varying T with R = 550 ft

Fig. 2 Cumulative number of false alarms.

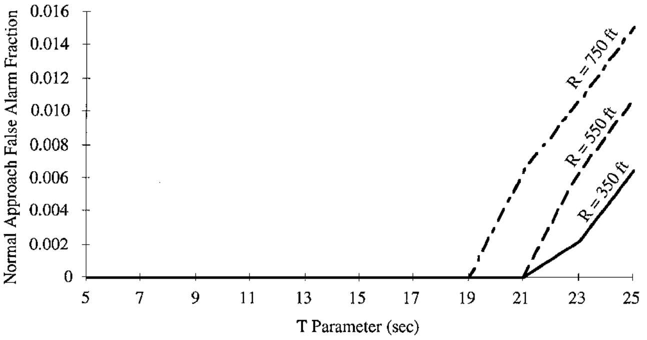
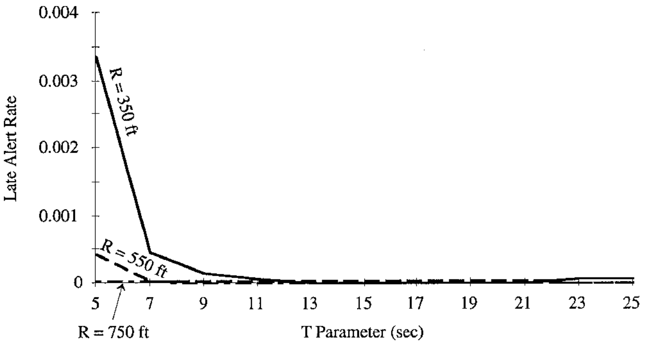
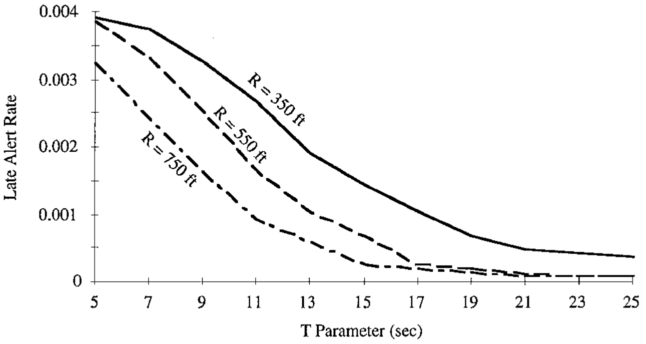


Fig. 3 Normal approach false alarm rate.

To examine the susceptibility of the system to producing false alarms during normal approaches, Fig. 3 plots the fraction of normal intruder approaches that result in false alarms as a function of R and T. For the $R = 350$-ft case, normal approach false alarms did not occur until T exceeded 21 s. For the maximum value of R of 750 ft, normal approach false alarms began to occur above $T = 19$ s. Thus, overall, AILS appears to give few true unnecessary alerts until



Climbing-turn



Climb-only

Fig. 4 Late alert rate.

the parameter values are increased well beyond nominal settings. However, because normal approaches were only a small fraction of the entire test trajectory set, these bounds must be considered rough estimates. A more thorough study of normal approach false alarms, with a better model of approach behavior, may be needed.

Note that Figs. 2 and 3 apply equally to the climbing-turn and the climb-only maneuvers, because the curves are functions of the parameters R and T only, and not of the escape maneuver.

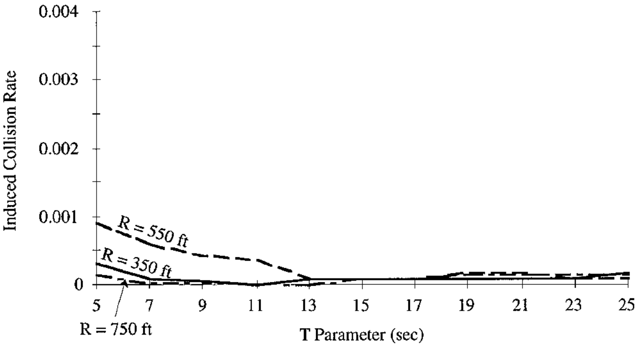
Collision Analysis

Figure 4 shows the fraction of all simulated trajectories that resulted in a collision because the system alerted too late (late alert) as a function of R, T, and the evasion maneuver. Increasing the values of either R or T decreases the rate of collisions. For the climbing turn, the nominal parameter values are such that late alerts occur at a negligible rate (see Table 2), a condition not equaled for any parameter values with the climb-only maneuver.

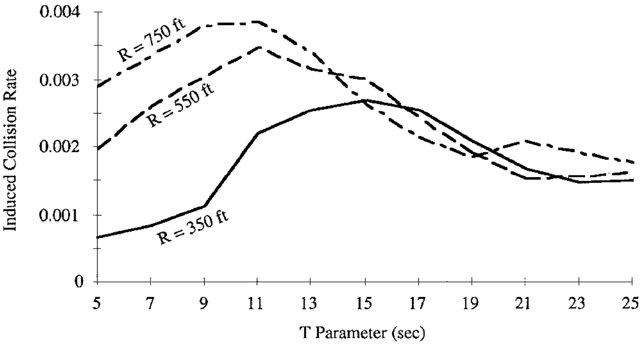
Figure 5 shows similar data for the induced collision rate. Once again, no values of R and T for the climb-only case attain performance equal to that of the climbing turn with nominal parameter values.

Note that the induced collision rate peaks for intermediate values of T in the climb-only case. This is because induced collisions are indicative of a deficiency in the trajectory model. For an induced collision to occur, the alerting system first fails by alerting when not necessary and then by not providing adequate separation to prevent a collision. For small values of T, trajectory extrapolation is shortened, and the alerting system is better able to distinguish true collision threats. However, there is correspondingly less time to escape, resulting in higher late alert rates, as shown in Fig. 4. At large values of T, the intruder is far enough away when an alert is issued that adequate separation is likely regardless of the trajectory the intruder follows. Intermediate values of T, however, are such that the trajectory extrapolation is perhaps too long relative to the uncertainties, and induced collisions become more likely.

Typical induced collision trajectories from the simulation are shown in Fig. 6. In Fig. 6a, an intruder initially travelling at 145 kn along the glide slope blunders by making a sudden 15-deg heading change, simultaneously accelerating to a 2000-ft/min final climb rate. An alert is not triggered aboard the host aircraft until the intruder is crossing the host's approach centerline, passing behind the host and just outside of the 500-ft collision threshold. Responding to the alert with a climbing-turn maneuver, the host accelerates toward and collides with the intruder a few hundred feet from the centerline. In Fig. 6b, an intruder travelling at 160 kn begins a 5-deg constant-bank turn and again accelerates vertically to 2000 ft/min. This time an alert occurs before the host's centerline is reached, but again the intruder passes behind the host. The collision occurs approximately 2000 ft from the centerline after the host has initiated a climbing-turn evasion maneuver. These incidents are typical of induced collisions that occurred with the climbing-turn maneuver in that they involve a climbing intruder's drifting slowly in the lateral direction. Induced collisions associated with the climb-only maneuver, not illustrated, are characterized by slight vertical accelerations by the host that bring the host into contact with an intruder that otherwise would have passed just overhead.



Climbing-turn



Climb-only

Fig. 5 Induced collision rate.

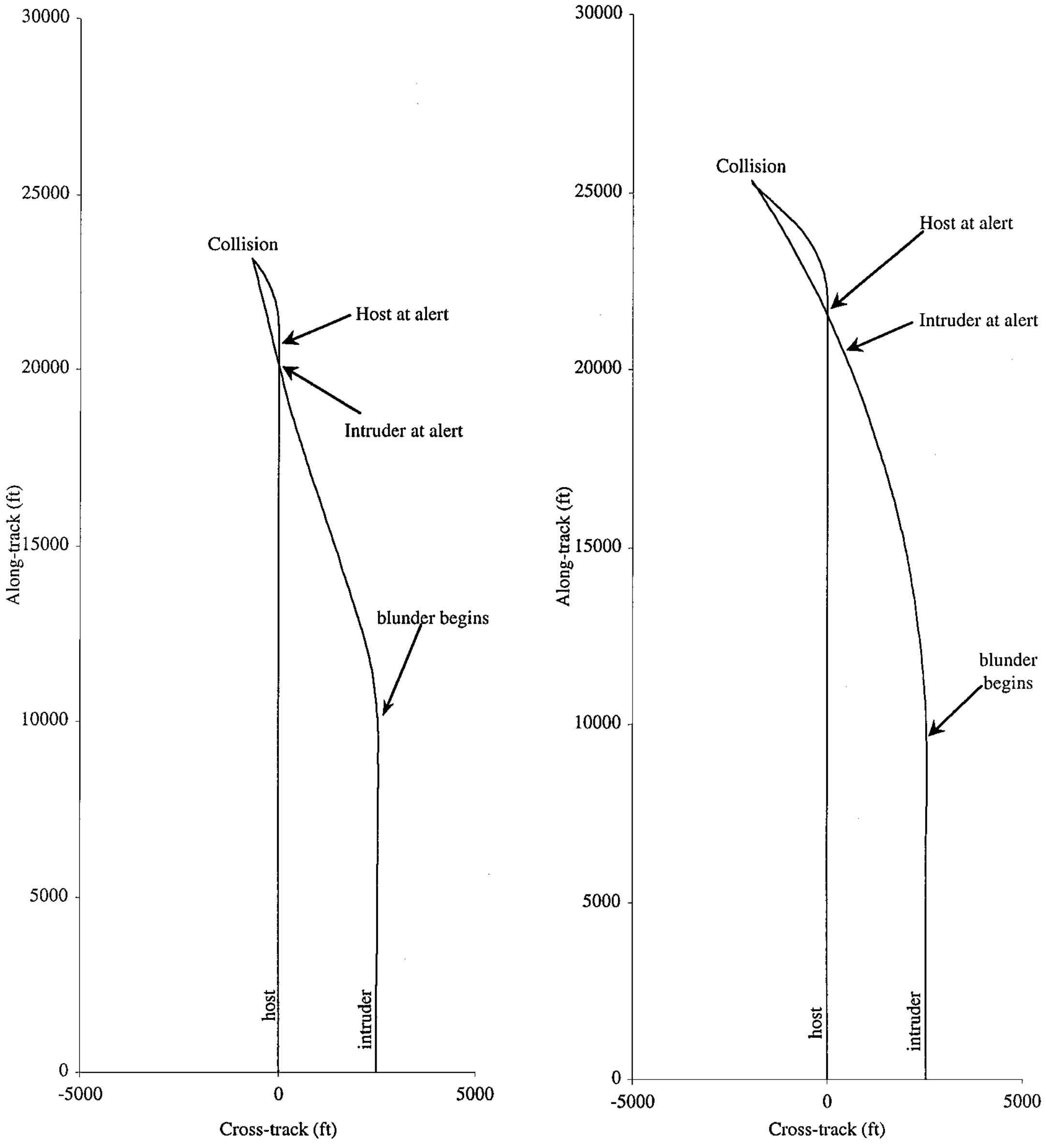
Response Time Effects

Another important issue is the speed with which a pilot responds to an alert. Both the climbing-turn and climb-only maneuvers were initially based on a 2-s pilot latency. This is an optimistic estimate compared with the 5 s allowed by both TCAS and GPWS.[7,8] It is therefore desirable to know how sensitive system performance is to changes in reaction time.

Simulations were run for both the climbing-turn and the climb-only evasions with the nominal values of R and T, with varying pilot reaction time. The results are shown in Fig. 7, in terms of the fraction of imminent collision blunder cases that were correctly resolved. The fraction of imminent collisions averted, f, can be determined for each maneuver with the expression

$$f = \frac{\mathrm{CD}}{\mathrm{MD} + \mathrm{CD} + \mathrm{LA}} \tag{1}$$

where CD, MD, and LA are the correct detection, missed detection, and late alert rates, respectively (see Table 2). For example, for a pilot response delay of 2 s, these values can be read directly from Table 2. It is clear from Fig. 7 both that the climbing turn is more robust with respect to reaction time and that performance of the climb-only maneuver is inferior even for perfect (zero) reaction time.



a) 15 deg Heading change blunder (145 kn) b) 5 deg Constant bank blunder (160 kn)

Fig. 6 Examples of induced collision trajectories.

System Operating Characteristic Curves

System operating characteristic (SOC) curves have been devised as a way directly to view the tradeoff between false alarms and collisions.[9] For a given threshold definition and blunder dynamics, the alerting system will have certain probabilities of false alarms and of successful system responses (anything not resulting in a collision). An SOC curve is a plot of the functional relationship between the two as one parameter of the alerting system is varied.

For the simulation used in this research it would be unreasonable to interpret the event fractions in Table 2 as the probabilities of those events, because blunders make up the vast majority of test trajectories, whereas in actual operation the opposite would be true. Furthermore, it is doubtful that all simulated blunder cases are equally likely, as a probabilistic interpretation of the numbers would implicitly assume.

A compromise is to normalize the totals of false alarms and successful alerts by the total number of alerts that were issued. In terms of the variables from Table 2, this can be expressed as

$$P(\text{FA}) = \frac{\text{UA} + \text{IC}}{\text{IC} + \text{UA} + \text{CD} + \text{LA} + \text{MD}} \qquad (2)$$

$$P(\text{SA}) = \frac{\text{UA} + \text{CD}}{\text{IC} + \text{UA} + \text{CD} + \text{LA} + \text{MD}} \qquad (3)$$

where UA, IC, CD, LA, and MD are the fractions of unnecessary alerts, induced collisions, correct detections, late alerts, and missed detections, respectively, that occurred over all intruder trajectories. The resulting quantities are interpreted as conditional probabilities, given that an alert has been issued. $P(\text{FA})$, as defined here, is then the probability that an issued alert is a false alarm. Note that by definition a false alarm is an alert that is issued when a collision would not have occurred had that alert not been generated. The second metric, $P(\text{SA})$, is the probability that an issued alert is successful in avoiding a collision. Thus $1-P(\text{FA})$ is the probability that a collision will occur without an alert, and $1-P(\text{SA})$ is the probability that a collision will occur with an alert. Plotting $P(\text{SA})$ vs $P(\text{FA})$ produces an SOC curve, such as in those shown in Fig. 8.

An ideal alerting system would have $P(\text{SA}) = 1$ and $P(\text{FA}) = 0$ and would therefore operate in the upper-left corner of the plot of Fig. 8. Operating points on a diagonal line of slope 1 through the origin represent conditions of no overall benefit. That is, alerting while on the diagonal line is equally likely to result in a collision as not alerting. At points below this diagonal, alerting is more likely to result in a collision than not alerting.

Figure 8 contains SOC curves for AILS, with each evasion maneuver as a function of the parameters R and T. For a given value of R, the system operating point will move to the right along each of the curves as the value of T is increased. Thus increasing T

generally increases both $P(\mathrm{SA})$ and $P(\mathrm{FA})$. The benefit of alerting is clearly apparent for the climbing-turn evasion, as all tested combinations of R and T place the operating point well above the diagonal. Nominal parameter values place the climbing-turn operating point at a $P(\mathrm{SA})$ of approximately 0.994, with a $P(\mathrm{FA})$ of approximately 0.713. In contrast, operating points for the climb-only evasion all lie within the vicinity of the diagonal, with $P(\mathrm{SA})$ lower than that for the climbing turn at each value of $P(\mathrm{FA})$. Settings of the threshold that produce a high $P(\mathrm{FA})$ cause the operating point to lie above the diagonal, but even at the maximim $P(\mathrm{FA})$ attained, $P(\mathrm{SA})$ is no higher than 0.97 (and for reasons that will be discussed, the parameter values that achieve this are not even feasible). In contrast, $P(\mathrm{SA})$ with the climbing turn is at 0.98 or above, even at smaller values of T. Because the set of blunder trajectories used in the simulation does not necessarily give an accurate probabilistic description, the numbers arising from the simulation may not be valid to the precision implied in the numbers above. However, it can be noted that the climbing turn provides a $P(\mathrm{SA})$ of nearly the desired value of 1 over a wide range of threshold settings, whereas the climb-only maneuver provides safety that is difficult to distinguish from having no alerting system at all.

Recall that normal approach false alarms are more important to avoid than false alarms that occur during blunders. Because the $P(\mathrm{FA})$ quantity lumps all false alarms together, it is not necessary to reduce $P(\mathrm{FA})$ to a negligible value, so long as normal approach false alarms do not occur. Normal approach false alarms begin to occur only for large values of T, as was illustrated in Fig. 3, and this places an upper bound on the acceptable T range. From Fig. 3, smaller R values allow larger values of T before normal approach false alarms become a problem. Therefore, depending on the choice of R, values for T above 19–21 must be avoided for the assumption of reliable execution of evasion maneuvers by pilots (which is implicit in the simulation) to be reasonable.

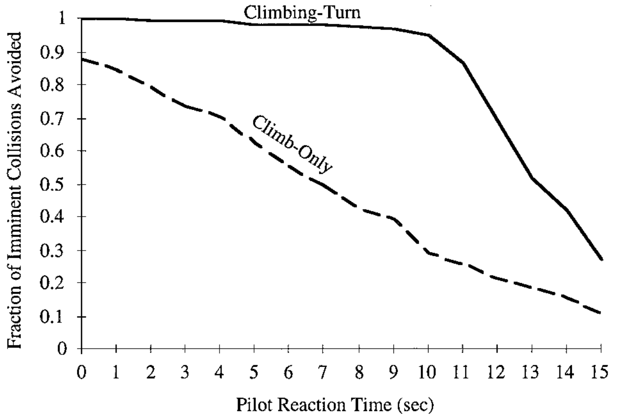


Fig. 7 Imminent collisions averted vs reaction time (R = 550 ft and T = 13 s).

As mentioned above, normal approaches made up only a small fraction of the total trajectory set used in the analysis described here, so the stated limiting values of R and T are probably overly optimistic. Further study is needed to describe the false alarm behavior of AILS more accurately and to determine the allowable ranges of R and T properly.

Conclusions

The analysis described above provides some insight into the relative performance of the two evasion maneuvers when used with the AILS alerting logic as of January 1998. Based on the results, the following conclusions can be made:

1) Over a range of blunder types and flight conditions at the nominal AILS alert threshold parameter values, the climb-only evasion maneuver was observed to result in approximately 38 times more collisions than the turning-climb evasion maneuver.

2) SOC curves show that the climb-only evasion maneuver results in a system that is of little benefit: Alerting provides approximately the same level of safety as not alerting, regardless of the threshold setting. In contrast, with a climbing-turn maneuver there is a significant safety benefit to producing an alert at some threshold settings.

3) The climbing-turn maneuver is less sensitive to pilot reaction time than the climb-only maneuver. The safety level provided by the climb-only maneuver degrades approximately 5 to 10 times more rapidly than the climbing-turn as pilot reaction time is increased.

For these reasons, it is believed that the climb-only evasion maneuver as assumed will not be adequate to provide sufficient safety at a 2500-ft runway spacing.

Acknowledgments

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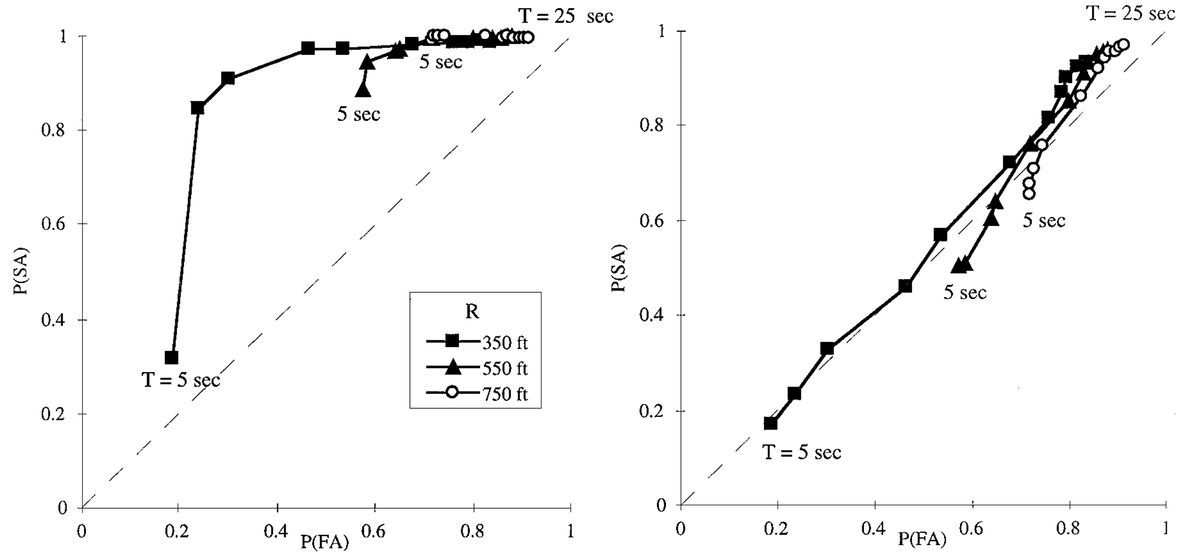
References

[1] Waller, M. C., and Scanlon, C. H., eds., *Proceedings of the NASA Workshop on Flight Deck Centered Parallel Runway Approaches in Instrument Meteorological Conditions*, NASA CP 10191, NASA, Hampton, VA, Dec. 1996.



Climbing-turn **Climb-only**

(T varied from 5 to 25 sec in 2 sec increments)

Fig. 8 SOC curves.

[2] Federal Aviation Administration, “Precision Runway Monitor Demonstration Report,” Document DOT/FAA/RD-91/5, Federal Aviation Administration, Washington, DC, Feb. 1991.

[3] Shank, E. M., and Hollister, K. M., “Precision Runway Monitor,” *Lincoln Laboratory Journal*, Vol. 7, No. 2, 1994, pp. 329–353.

[4] Koczo, S., “Coordinated Parallel Runway Approaches,” NASA CR NAS1-19704—Task 11, Hampton, VA, May 1996.

[5] Carpenter, B. D., and Kuchar, J. K., “A Probability-Based Alerting Logic for Aircraft on Parallel Approach,” NASA CR 201685, Hampton, VA, April 1997.

[6] Kuchar, J. K., and Carpenter, B. D., “Airborne Collision Alerting Logic for Closely-Spaced Parallel Approach,” *Air Traffic Control Quarterly*, Vol. 5, No. 2, 1997, pp. 111–127.

[7] Radio Technical Committee for Aeronautics (RTCA), “Minimum Performance Specifications for TCAS Airborne Equipment,” Document RTCA/DO-185, Radio Technical Committee for Aeronautics, Washington, DC, Sept. 1983.

[8] Radio Technical Committee for Aeronautics (RTCA), “Minimum Performance Standards—Airborne Ground Proximity Warning Equipment,” Document RTCA/DO-161A, Radio Technical Committee for Aeronautics, Washington, DC, May 1976.

[9] Kuchar, J. K., “Methodology for Alerting-System Performance Evaluation,” *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 19, No. 2, 1996, pp. 438–444.