Project Report
ATC-226

Safety Analysis of the Traffic Information Service

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22 November 1994

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Prepared for the Federal Aviation Administration,
Washington, D.C. 20591

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. ATC-226	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Safety Analysis of the Traffic Information Service	5. Report Date 22 November 1994
	6. Performing Organization Code
7. Author(s) Divya C. Chandra and M. Loren Wood	8. Performing Organization Report No. ATC-226
9. Performing Organization Name and Address Lincoln Laboratory, MIT P.O. Box 73 Lexington, MA 02173-9108	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DTFA01-93-Z-02012
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, DC 20591	13. Type of Report and Period Covered
	14. Sponsoring Agency Code

15. Supplementary Notes

This report is based on studies performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology. The work was sponsored by the Air Force under Contract F19628-95-C-0002.

16. Abstract

Traffic Information Service (TIS) is a Mode S data link application being developed for use by general aviation (GA) pilots. Its purpose is to provide a low-cost means of assisting the pilot in visual acquisition of nearby aircraft. The service provides two functions: traffic alerting and threat assessment. These functions are also performed by the Traffic Alert and Collision Avoidance System (TCAS).

The purpose of this report is to evaluate the effectiveness and safety of TIS in relation to that of TCAS I. The analysis begins with a conceptual review of Andrews' statistical model of visual acquisition. Next, the surveillance systems and threat-detection logic of TIS and TCAS I are reviewed. Results of a Monte Carlo simulation that modeled the threat-assessment performance of TCAS I and TIS are also presented. The analysis supports the conclusion that, because of the high degree of similarity between TIS and TCAS I, TIS is a safe and effective means of assisting the pilot in visual acquisition of air traffic.

17. Key Words traffic alert and collision avoidance system (TCAS) cockpit display of traffic information (CDTI) data link visual acquisition threat assessment	18. Distribution Statement This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 46	22. Price

FORM DOT F 1700.7 (8-72) Reproduction of completed page authorized

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1. INTRODUCTION

Pilots of general aviation (GA) aircraft primarily depend on the "see and avoid" principle of collision avoidance when flying under visual flight rules (VFR). According to this principle, they are responsible for conducting regular, conscious, and effortful visual searches for nearby traffic. If traffic is sighted, the pilot must develop and execute a plan to avoid the other aircraft. Air traffic controllers sometimes alert GA pilots to nearby air traffic by delivering traffic advisories. Controllers who disseminate traffic advisories to GA pilots do so on a "workload permitting" basis. As such, delivery of these advisories is intermittent and, unfortunately, GA pilots are least likely to receive verbal traffic advisories when large numbers of aircraft are in the vicinity.

Traffic Information Service (TIS) is a Mode S data link application being developed for use by GA pilots. It is designed to provide the pilot with a more continuous stream of traffic information than the controller can verbally provide. The service will be available to all suitably equipped aircraft under Mode S surveillance. The primary goal of TIS is to provide a low-cost means of assisting the GA pilot in visual acquisition of air traffic. Its name, "Traffic Information Service," is intended to reinforce the concept that TIS is to be used as a source of traffic *information* rather than as a source of *guidance* for resolving the conflict situation. The system, which is automated, accomplishes this goal without increasing workload for air traffic controllers and without requiring installation of new equipment in intruder aircraft.

The problems of visual acquisition and collision avoidance were explored in detail during the development of the Traffic Alert and Collision Avoidance System (TCAS) and its experimental predecessor, the Intermittent Positive Control (IPC) Pilot Warning Instruments (PWI) system. TCAS is now available in two forms, TCAS I and TCAS II. (See Harman [1] for a review of TCAS development.) TCAS I is used only for traffic alerting and threat assessment. TCAS II is a more advanced system that provides conflict resolution advisories (RAs) in addition to traffic alerting and threat assessment. The RA feature of TCAS II makes it a much more complex (and costly) system than either TIS or TCAS I. TCAS I and TCAS II employ the same threat-detection logic, which is based on information from virtually identical surveillance systems; therefore, they have equivalent traffic-alerting and threat-assessment capabilities. The expense of TCAS II, however, prohibits its installation on most GA aircraft; the cost of TCAS II avionics exceeds the total value of a typical light aircraft.

Traffic Information Service is designed to be a low cost system that emulates those features of TCAS equipment that yield the greatest enhancements in visual acquisition. To this end, TIS functions in a manner similar to TCAS I: Both systems provide a display of nearby traffic and an audible alert if an intruder aircraft is detected as a collision threat. TCAS equipment provides a graphical color display of proximate traffic; a similar color display is preferred for TIS. However, monochrome graphic displays and text displays of traffic are permitted for TIS [2, 3], primarily because of their low cost relative to color displays. (The issue of display type will be examined further below.)

The purpose of this report is to analyze the effectiveness and safety of TIS in relation to that of TCAS I. This comparison is appropriate because both systems perform the same functions, viz. traffic alerting and threat assessment. Although TIS and TCAS I provide similar information to the pilot, their sources of information differ. The surveillance system of TCAS I is airborne and self-contained, while TIS obtains information from ground-based Mode S sensors. Hence, overall system performance must be compared for both functions. The analysis supports the conclusion that, because of the high degree of similarity between TIS and TCAS I, TIS is a safe and effective means of assisting the pilot in visual acquisition of air traffic.

This report is organized into three parts. The first section contains a conceptual review of Andrews' statistical model of visual acquisition [4]. In the second part, the surveillance systems of TCAS I and TIS are reviewed and the threat-detection logic employed by both systems is described. Features of TIS that differ from TCAS I are emphasized. The third segment of this report discusses results of a Monte-Carlo simulation that was developed to assess the differences in threat-assessment performance between TIS and TCAS I. Threat-assessment performance is evaluated both in terms of accuracy and timeliness.

2. VISUAL ACQUISITION

There are three components to the task of collision avoidance: surveillance, threat assessment, and conflict resolution. When a human is conducting "surveillance," the task is called "visual search." In fact, visual acquisition is the weak link in the chain of events that comprise collision avoidance. As Andrews [4] points out, although there are documented cases of poor conflict-resolution choices, "In most cases where see-and-avoid fails it appears that 'seeing' (acquisition) either did not occur or occurred too late for effective pilot reaction" (p. 3). The pilot assesses the degree of threat immediately upon visual acquisition. Still, visual acquisition should be accomplished as early as possible to allow the pilot time to devise and execute a plan for avoiding the intruder.

A traffic advisory from an air traffic controller is a significant aid for visual acquisition in two respects. First, it alerts the pilot to the existence of traffic. The pilot's response to the alert, in general, is to increase his/her efforts on the search task. Second, the advisory usually informs the pilot in which direction to look for the traffic; this information increases search efficacy by reducing the field of view to be scanned. The controller conveys the direction of search in terms of clock positions (where 12 o'clock denotes "straight ahead" in the pilot's field of view, and 6 o'clock is "directly behind"). The pilot translates the clock position (i.e., relative bearing) into a gaze direction. Because pilots know that a clock position is only a rough estimate of the traffic's location,[1] they tend to search a broad (60 degrees to 90 degrees) sector centered around the specified direction [4]. Even if the information were more precise, pilots would have difficulty in choosing a precise gaze direction due to natural variance in human performance.

Andrews has developed and verified a statistical model of visual acquisition over the course of several studies [4-8]. The ultimate aim of his model is to describe visual acquisition in terms of the probability of sighting an aircraft within bounding conditions (specified in terms of time or range). The model takes into account both the physical parameters that encode the geometry of the encounter and human parameters. At the core of the model is an equation for the instantaneous rate of visual acquisition (λ), which is a function of several parameters that vary in time. The formula for λ is integrated to obtain the probability of acquisition within the specified bounds. Because λ is allowed to vary with time, the function describes a nonhomogeneous Poisson process. (A classic, homogeneous Poisson process requires a constant λ.)

At a conceptual level, the full form of Andrews model contains three terms (see Eq. 1). The first term (β) is an empirically-derived parameter that accounts for the effectiveness of the pilot's visual search; pilots whose search efficacy is high (e.g., an alerted pilot) are modeled with high values of β. The second term is the visible (cross-sectional) area of the target (A) scaled by the square of the range to the target (r^2); this term denotes the size of the target in the pilot's field of

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[1] Each clock position refers to a 30-degree segment of the 360 degrees surrounding the pilot. The controller does not have enough information on the ground to specify a precise relative bearing. In order to do so, the controller would have to know both the ground tracks of the two aircraft *and* the crab angle of the aircraft in which the advised pilot is flying. Because crab angles are typically less than 30 degrees and because controllers do know the ground tracks of the two aircraft, a clock position is a reasonably accurate estimate of the intruder's position in the advised pilot's field of view.

view.[2] The remaining (exponential) term contains the ratio of the range to the target (r) and visual range (R); this term accounts for degradation of target detectability caused by atmospheric parameters.

$$\lambda = \beta\left(\frac{A}{r^2}\right)e^{\left(\frac{-2.996r}{R}\right)} \qquad \text{(Eq. 1)}$$

Andrews has obtained values for β under a variety of conditions; these values are compiled in Table 1. Notice that the value of β for alerted search is roughly eight times higher than its value for unalerted search. (The only exception is the case where pilots were attempting to follow conflict-resolution procedures suggested by the Pilot Warning Instruments; having a separate conflict-resolution task to perform detracted from pilots' performance on the visual search task.) Thus, β behaves in a logical manner: when pilots are alerted, λ (which corresponds to the probability of acquisition) increases. If the pilot fails to perform visual search, the value of β is set to zero, which correctly predicts that the probability of visual acquisition is zero.[3]

Table 1. Empirically-derived values of β.

Condition	β (1/ster-sec)	Citation
Unalerted GA pilots	1.1×10^4	[4]
	1.7×10^4	[5]
Alerted by PWI	9.0×10^4	[4]
With PWI commands	3.4×10^4	[4]
Alerted (known intruder path)	7.4×10^4	[4]
Alerted by TCAS II	1.4×10^5	[5]
	1.3×10^5	[7]

The eight-fold improvement in β for an alerted pilot is an oft-cited result. The primary causes of this improvement are less well known. Andrews himself attributes the bulk of the increase to two factors: increased effort and time devoted to the search task, and a reduction in the area to be searched [5]. In terms of these two factors, all traffic advisories are highly effective, be they from a ground-based controller, TCAS I/TCAS II, or TIS. An important advantage of electronic displays of traffic information over verbal advisories is that visual information on the (graphical or textual) display is available to the pilot longer than verbal information. The sustained

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[2] Readers who are familiar with the concept of visual angle should note that the resulting term (A/r^2) represents the "visual area" subtended by the traffic aircraft in the pilot's field of view. Visual area is a natural extension of the concept of visual angle.

[3] The failure to perform a visual search may occur because the pilot is distracted with another flight task (cf. Andrews, 1989), or simply because the pilot is lax. In other situations, the geometry of the aircraft paths and the relative speeds of the aircraft combine to make visual acquisition difficult even when the pilot is concentrating on the task; this type of poor performance is predicted by small values of visible area (A) or large values of range (r).

nature of electronic position reporting allows the pilot to monitor and adjust the visual search for changes in relative bearing.

Because search direction is given more *precisely* in the electronic displays, in theory, these systems are also "better" than a controller-delivered advisory because they allow the pilot to reduced his/her field of search even further. However, in order to take advantage of the extra precision of the electronic format, the pilot must change his/her search behavior correspondingly. The authors are unaware of any evidence that pilots do in fact change the size of their search field as a function of the precision of the information they are given. The precision with which humans can choose to gaze in a specified angular direction also has not been established. (Nor has it been established whether graphical displays produce more accurate human performance in terms of choosing a gaze direction than text displays.) The conservative approach, which pilots tend to apply, is to search a fairly broad sector (e.g., 60 degrees) around the indicated target direction. This is a reasonable strategy given that the incremental improvement achieved by narrowing the search region to adjust for more precise relative-bearing information is of diminishing returns.[4] Also, the conservative strategy reduces the chance of missing an intruder who is outside of the pilot's region of visual search. As long as the pilot is informed of the existence of proximate traffic and a gaze direction is specified, the probability of visual acquisition rises sharply.

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[4] The gain in performance achieved by reducing the field of search from 30 degrees ("some" information) to 15 degrees ("more precise" information) is small compared to the increase in performance obtained by narrowing the search field from 180 degrees (a realistic "no information" condition) to 30 degrees (with "some" information).

3. TCAS I AND TIS SYSTEM DESCRIPTIONS

Development of electronic technology to convey traffic information was a natural direction in which to proceed given the limitations on effective visual search and the high workload demands placed on air traffic controllers. TIS and TCAS I both assist the pilot in surveillance and threat assessment, but as mentioned earlier, the systems obtain information from different sources. A more complete description of the surveillance systems for both TCAS[5] and TIS is given below. The threat-detection logic, which is similar for TIS and TCAS is also presented.

3.1 SURVEILLANCE

Because TCAS is an airborne system, its internal coordinate system is in aircraft coordinates. To conduct surveillance, TCAS transmits interrogations (one per second) and detects replies from transponders on nearby aircraft (i.e., aircraft within 15 miles of the transmitting TCAS). Three types of surveillance data are obtained: range to the responding aircraft, altitude of the responding aircraft, and azimuth (i.e., relative bearing) of the responding aircraft.

The information obtained by TCAS is presented to the pilot in a graphical format (see Figure 1). Ownship is located at the center of a range ring on the display and each responding (traffic) aircraft is plotted in polar coordinates such that bearing information is preserved and range information is scaled appropriately. TCAS displays the measured relative bearing of traffic aircraft. As ownship turns, the positions of nearby aircraft are adjusted accordingly. Because interrogations are made each second, the update rate is 1 Hz. Note that because the display is oriented in terms of ownship heading, the relative bearings of other aircraft correspond directly to their positions in the pilot's field of view. Relative altitude of the traffic aircraft is given in hundreds of feet and is written above or below each symbol. The symbol for a intruder aircraft is coded by color and shape: a white diamond conveys proximity alert (i.e., an aircraft in the vicinity) and a yellow circle indicates a traffic alert (i.e., the aircraft is a potential threat).[6] A proximate aircraft that is "very close" to the aircraft in terms of time and distance is considered to be a "potential threat." (Details of the threat-assessment logic are presented in Section 3.2.)

The graphical display of TIS is identical to that of TCAS I. In the current implementation, traffic within 5 nautical miles and ±1200 feet altitude of the requesting aircraft is displayed. Proximate aircraft of known altitude are denoted by white diamonds and their relative altitudes are shown in hundreds of feet (as shown in Figure 1). A proximate aircraft whose altitude is unknown is denoted by a diamond outline. When a proximate aircraft is declared as a collision threat, TIS sounds an audible alert and (on the color display) the traffic symbol changes from a white diamond to a yellow circle. (On the monochrome display, the shape of the traffic symbol changes from a diamond to a square when the aircraft is declared as a threat.) The system does not provide any other guidance to the pilot in a threat situation.

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[5] Because the surveillance systems of TCAS I and TCAS II are virtually identical, the generic identifier "TCAS" will be used.

[6] Only white and yellow symbols are shown on TCAS I and TIS. On TCAS II a red symbol indicates that an resolution advisory has been issued for that intruder.

Figure 1. Color graphical display of traffic information.

Whereas TCAS is an airborne system that constantly monitors nearby traffic, TIS is a ground-based system that is only available when the requesting aircraft is under Mode S surveillance. The requesting aircraft must be equipped with a Mode S transponder and a Control and Display Unit (CDU), as shown in Figure 2. (When the service is unavailable, the pilot is informed of the situation by a message to that effect on the graphical display.) Algorithms for TIS are incorporated in the Mode S sensor and are therefore based on a ground coordinate frame. After a data link connection is established with a given aircraft, the Mode S surveillance track files are evaluated on each scan to determine the locations of traffic aircraft relative to the requesting aircraft. The trajectories of the traffic aircraft are then checked to determine whether the traffic poses a collision threat to the requesting aircraft. The intruder's ground track is relayed to the requesting aircraft. If the requesting aircraft has an onboard directional gyroscope, the onboard TIS algorithms can compensate for the requesting aircraft's crab angle and then present the location of the traffic in the pilot's field of view. (This allows the pilot to interpret the location of the target on the display directly as a search direction.) If the crab angle is not taken into account, the difficulty of the pilot's search task may be increased (depending on the magnitude of the crab angle).

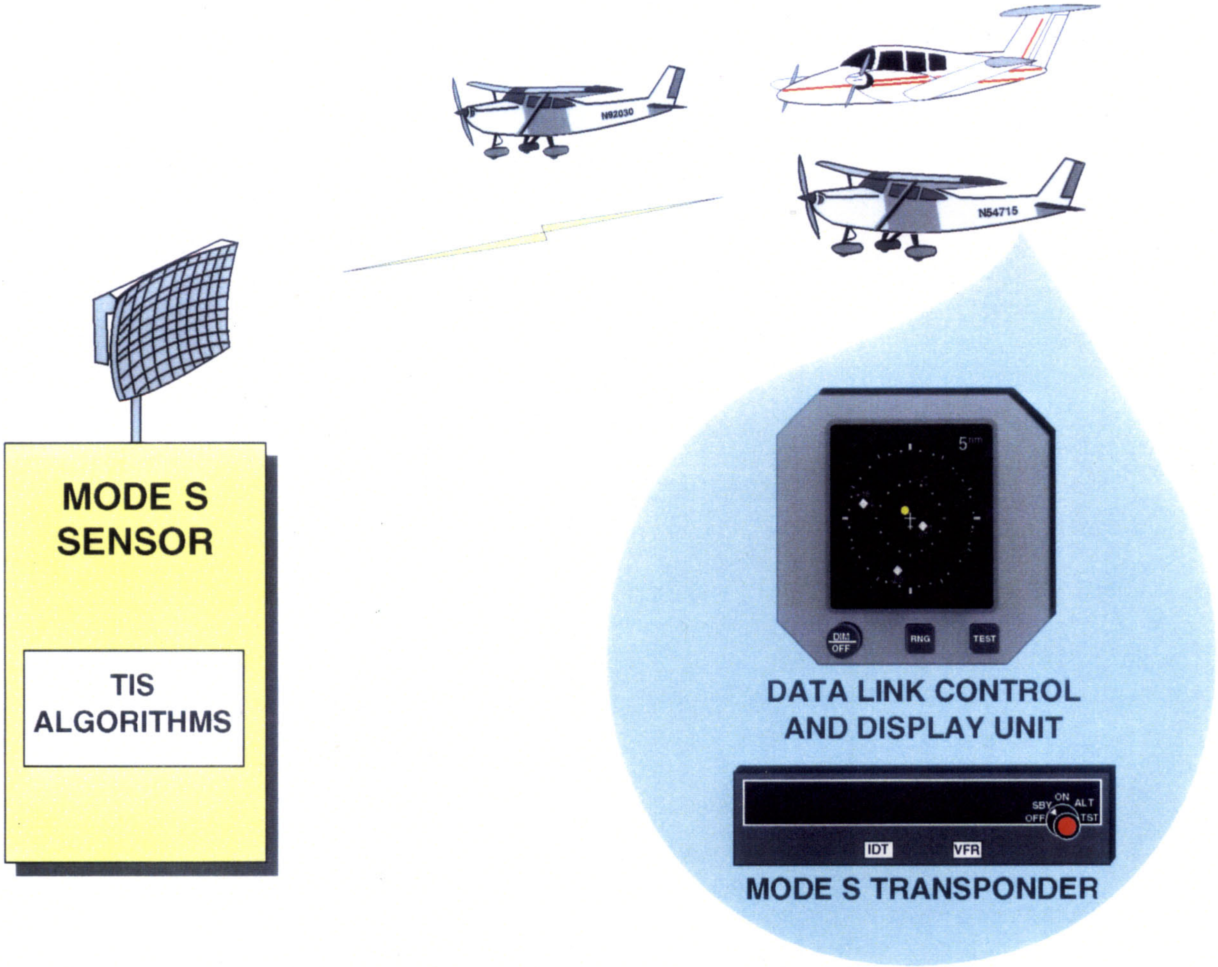

Figure 2. Airborne equipment and ground systems necessary for TIS.

Aside from the change in internal coordinate frames, the reliance of TIS on the Mode S sensor also has other consequences. One consequence is that the update rate of the airborne display is limited by the scan time of the radar, which is approximately five seconds. To compensate for its slow update rate, TIS uses aircraft velocities to predict locations one scan ahead in time; the predicted information is shown on the airborne display unit. (Parameters for the TIS alpha-beta tracker, which is used in the horizontal plane, are given in Appendix A. TIS employs the TCAS altitude tracker in the vertical plane [9].) Another consequence of the use of the Mode S sensor is that timely delivery via the data link system requires that the relayed information be quantized into a small number of bits (56), which constrains the precision of the surveillance information that can be sent. Bearing information is quantized into 6-degree intervals (thus requiring a maximum of 6 bits) and range information is sent in a nonlinear scale that requires

4 bits.[7] (Range information is transmitted in one-quarter mile intervals for values under 2 miles, and more coarsely thereafter out to a range of 7 miles.) The quantization of bearing angle into 6-degree intervals is not expected to affect the utility of the display because, as noted earlier, pilots tend to search a "broad" region (typically 60-degree) around the specified search direction. Quantization of the range information is also reasonable because range information is of secondary importance (to relative bearing) for visual acquisition.

3.2 THREAT-DETECTION LOGIC

The threat-detection algorithm for TIS is similar to that of TCAS. The essence of the logic is to declare a threat when either (1) the proximate traffic's range and closure rate are such that the pilot would have only a short time (30 seconds) to plan and execute a resolution procedure, or (2) the traffic is close enough to justify a threat declaration regardless of its closure rate. Specifically, a threat condition is declared if *both* of the following statements are true:

(1) the time to the point of closest approach (in the horizontal plane) is less than a critical value (τ) *or* the range between the two aircraft is less than a critical value, R_{min}

(2) the time to the point of closest approach (in the vertical plane) is less than a critical value (τ) *or* the altitude separation between the two aircraft is less than a critical value, Alt_{min}

For both TIS and TCAS, R_{min} is nominally set to 0.5 nm and Alt_{min} is set to 800 feet. The use of the R_{min} parameter creates a buffer zone that allows for tracker inaccuracies.

In the horizontal plane, the critical value τ is calculated as

$$\tau = -\text{(range / range rate)} \qquad \text{(Eq. 2)}$$

The horizontal plane (range) τ parameter is employed by both TIS and TCAS. In the vertical plane, TIS employs an "altitude τ", which is –(altitude / altitude rate), but TCAS does not. The values of both the range and altitude τ for TIS are set to 34 seconds. For TCAS, the range τ is set at 30 seconds. The value of τ for TIS is larger than its value for TCAS in order to compensate for the delay between the time of the threat computation on the ground and the time that the pilot views the alert in the air. (The transmission time may range from 0 to 4.8 seconds for a terminal area sensor.) A more complete explanation of the choice of the τ for TIS is given in Section 4.

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[7] There are two other reasons that a 6-degree quantization of bearing information is employed. First, 6-degree quantization is about the best accuracy that can be achieved by the TIS algorithm (due to 5-second updates and tracker inaccuracies). Also, on the graphical display used in our current implementation, the combination of display resolution and symbol size is such that finer quantization of the bearing information is not readily interpretable.

4. MONTE-CARLO SIMULATION OF THREAT ASSESSMENT

A Monte-Carlo simulation was developed in order to assess the differences in threat-assessment performance between TIS and TCAS. The simulation sets up a true encounter scenario and emulates the performance of both TIS and TCAS in surveillance and threat assessment. (Note once again that TCAS I and TCAS II have identical surveillance equipment; hence the generic identifier "TCAS" is used.) The simulation is used to evaluate threat-assessment performance in the horizontal plane only. The encounter geometry is configured such that the TIS-equipped aircraft is between 1 and 100 nm from the Mode S sensor (at any bearing) and moves along a straight line path. The traffic aircraft is allowed to turn (with small probability) for short durations (15 seconds). Measurements of both TIS and TCAS are noisy. A Gaussian noise of 5-degree standard deviation is added to the azimuth measurements of TCAS; for TIS, the azimuth noise is of 0.05-degree standard deviation. These noise distributions reflect the fact that azimuth error is more pronounced for TCAS than it is for the Mode S sensor. Range measurements of TCAS are quantized to intervals of 62.5 feet and range measurements for TIS are quantized to 47.5 feet; these values produce a distribution of range measurements with a standard deviation of roughly 25 feet for both TCAS and TIS. The parameters for TIS measurement accuracy in both azimuth and range are those of the Mode S sensor.

For each encounter situation, the software records whether TIS and TCAS alarmed (or did not) as appropriate. The time at which the alarm was declared is also recorded. Accuracy data are reported in terms of hits, misses, false alarms (FAs), and correct rejections (CRs), as defined in Table 2. A hit occurs when the system declares a threat and the true encounter is a threat situation. A miss occurs when the system does not declare a threat when in fact a threat does exist. Similarly, a false alarm is an error in that a threat was declared where none existed and a correct rejection is a correct assessment that no threat exists. With this taxonomy, a simple nonparametric estimate of system performance is it overall accuracy, which is computed as follows:

$$\text{accuracy} = (\text{Hits} + \text{CRs}) \,/\, (\text{total number of encounters}) \qquad \text{(Eq. 3)}$$

where

$$\text{total number of encounters} = \text{Hits} + \text{CRs} + \text{FAs} + \text{Misses} \qquad \text{(Eq. 4)}$$

Table 2. Classification of threat assessments.

	Declaration	
	Threat	Nonthreat
"True" threat	Hit	Miss
"True" nonthreat	False Alarm (FA)	Correct Rejection (CR)

Two questions were addressed using the simulation. First, how *accurate* is the threat-detection logic of TIS in relation to that of TCAS? Second, does TIS generate alerts at the same *time* that TCAS does? Ideally, TIS will mimic the performance of TCAS. The accuracy of TIS is expected to vary with the choice of its parameters, τ and R_{min}.[8] In order to answer the first question, R_{min} and τ (for TIS) were varied independently of one another, and the accuracy was examined. To answer the second question, TIS τ was varied with TIS R_{min} held constant. For each of the simulation runs, the performance of TIS and TCAS is recorded. No TCAS parameters were manipulated, so the variation in TCAS performance across the different simulation runs is due to chance. The results of these analyses are presented in Sections 4.1 and 4.2 . Raw data from the simulation runs are given in Appendix B.

4.1 ACCURACY OF THREAT ASSESSMENT

Our first goal was to determine the accuracy of the TIS algorithm in threat assessment as compared against the TCAS algorithm. To accomplish this goal, the simulation was first tested at a range of values for TIS R_{min} while holding TIS τ constant. The nominal value for TIS τ was chosen to be 34 seconds; TIS R_{min} was varied from 0.3 nm to 0.8 nm in 0.1 nm increments. Each condition was tested over 1000 encounters where an encounter consisted of 100 time steps. (Each time step is 1 second.) The results indicate that the value of TIS R_{min} is not a strong determinant of accuracy (see Table 3). On the basis of these results, the value of R_{min} for TIS was chosen to be 0.5 nm, one of the two values which yielded the best accuracy (93.1%). On average, however, the accuracy of TIS was slightly lower than that of TCAS (92.5% versus 98.2%).

The simulation was also run at four different values of TIS τ (32 seconds, 33 seconds, 34 seconds, and 35 seconds) while holding TIS R_{min} constant at 0.5 nm. For these cases, the percent of correct responses ranged from 94.7% to 92.5% as shown in Table 4. Again, overall TIS performance was slightly less accurate than that of TCAS (94% versus 98%). Of the different values of TIS τ, 35 seconds produced the least accurate performance. The other values of TIS τ produce nearly equivalent performance.[9]

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[8] There may also be interactive effects due to the specific combination of τ and R_{min} chosen, but these are of secondary importance.

[9] To test for statistically significant differences between the different τ values, we need a measure of the variability in performance due to chance. With the data that we have, one choice for such a measure is the standard deviation of TCAS performance. Because no TCAS parameters were varied, variation in TCAS performance was purely due to chance. If a normal distribution of system accuracy is assumed, 98% of the obtained accuracies will fall within a range of three times the value of the standard deviation. Because TCAS performance had a mean of 0.98 and a standard deviation of 0.005, obtained accuracy is expected to fall between 0.98 ± 0.015. If TIS performance also has a standard deviation of approximately 0.005, obtained accuracies between 0.94 ± 0.015 are possible. Hence, the difference in performance between τ of 32, 33, and 34 seconds is not significant.

Table 3. Accuracy of TIS threat assessment as a function of TIS R_{min}. Each value of R_{min} was tested over 1000 encounters. Across the 5000 encounters represented here, TCAS averaged 98.1% correct with a standard deviation of 0.4%. The value of the TIS τ parameter is constant at 34 seconds.

TIS R_{min} (nm)	TIS % correct
0.3	92.0
0.4	93.1
0.5	93.1
0.6	92.3
0.7	91.9
0.8	89.4

Table 4. Accuracy of TIS threat assessment as a function of TIS τ. Each value of τ was tested over 1000 encounters. Across the 4000 encounters represented here, TCAS averaged 98.0% correct with a standard deviation of 0.5%. The value of the TIS R_{min} parameter is constant at 0.5 nm.

TIS τ (seconds)	TIS % correct
32	94.7
33	94.6
34	94.2
35	92.5

Another factor that might influence the accuracy of TIS threat assessment is the range between the two aircraft (requesting and intruder) and the Mode S sensor. For both TIS and TCAS equipment, larger distances between the aircraft and the sensor produce larger errors in position measurement. However, TCAS equipment only assesses replies from aircraft within 15 miles of the interrogating system whereas the Mode S sensor for TIS may be up to 100 miles away from the two aircraft (as modeled in the simulation). Hence, errors in position measurement may be much larger for TIS when the aircraft are far from the sensor. The decreased accuracy of measurement may cause the reduction in TIS threat-assessment accuracy. In order to test for this effect, two simulation runs were performed, one in which the aircraft were "close" to the sensor (i.e., between 1 and 20 nm away) and another in which the aircraft were "far" from the sensor (i.e., between 80 and 100 nm away). The value of TIS R_{min} for these runs was 0.5 nm; the value of TIS τ was 34 seconds. When the aircraft were close to the sensor, the accuracy of TIS threat assessment was 93.8% and when the aircraft were far from the sensor, the accuracy was 93.6%; this is a nonsignificant effect. (The accuracy of the TCAS algorithms for these runs was 96.8%

and 99.0%.[10]) Hence, range to the sensor does not explain the slight reduction in accuracy of TIS threat assessments.

4.2 TIMING OF THREAT DECLARATIONS

In the cases where both TIS and TCAS declared a threat, the timing of the alerts may be compared. The value of τ is more directly related to the time of the alert than is R_{min}, so data from the simulation runs in which τ was varied are examined. Means and standard deviations of alert times for both TIS and TCAS are compiled in Table 5. Note that only the TIS values of τ were manipulated, so the variation in TCAS performance is random. Alarm-time data from these runs are plotted in Figures 3 through 6. Two distributions are plotted in each of these figures, one of TCAS alarm times and one of TIS alarm times. The distributions of the *difference* in alarm time (between TIS and TCAS) for these same runs are shown in Figures 7 through 10. Alarm time differences of less than five seconds are not significant for TIS because of the inherent one-scan data link delay. (Note that the mean difference in alarm times is equal to the difference of the mean alarm times, but the standard deviation of the difference distribution does not equal the average of the individual standard deviations.) Examination of these figures reveals that 34 seconds is an appropriate choice for the value of the TIS τ parameter, although 33 seconds is also a reasonable choice. The value of 34 seconds yields a moderate delay in alarm time (relative to other values of TIS τ) in combination with a moderate standard deviation.

Table 5. Relative time of alarm for TIS and TCAS in seconds (referenced to a nominal alarm time of 30 seconds prior to the point of closest approach). Positive values denote that the alarm time was *late* relative to the nominal alarm time. Note that only the TIS value of τ was varied; TCAS performance was not manipulated.

	TCAS		TIS		Difference	
TIS τ (sec)	Mean (sec)	Stdev (sec)	Mean (sec)	Stdev (sec)	Mean (sec)	Stdev (sec)
32	2.33	5.02	5.85	5.89	3.52	4.15
33	1.92	3.44	4.23	6.40	2.31	5.54
34	2.44	4.76	4.75	6.24	2.31	4.45
35	2.11	4.47	3.19	6.84	1.08	5.29

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[10] These accuracy values for the TCAS algorithms are within their expected range as given in the previous footnote.

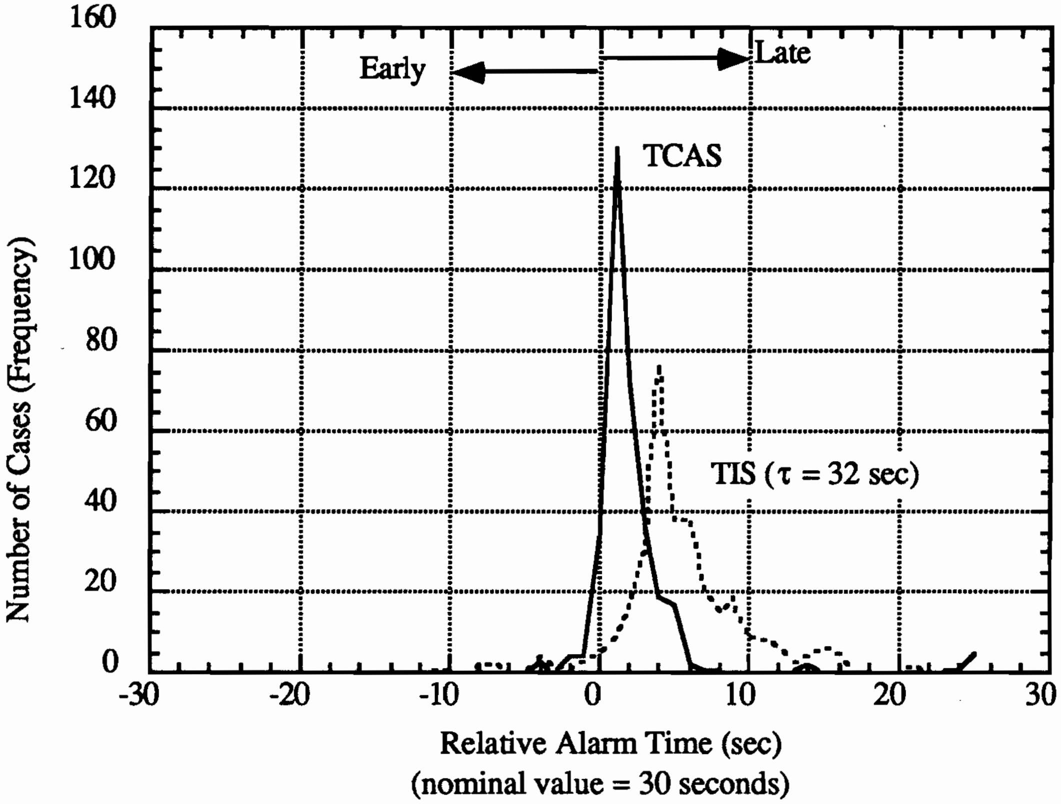

Figure 3. TIS and TCAS alarm times relative to nominal alarm time. TIS τ set to 32 seconds.

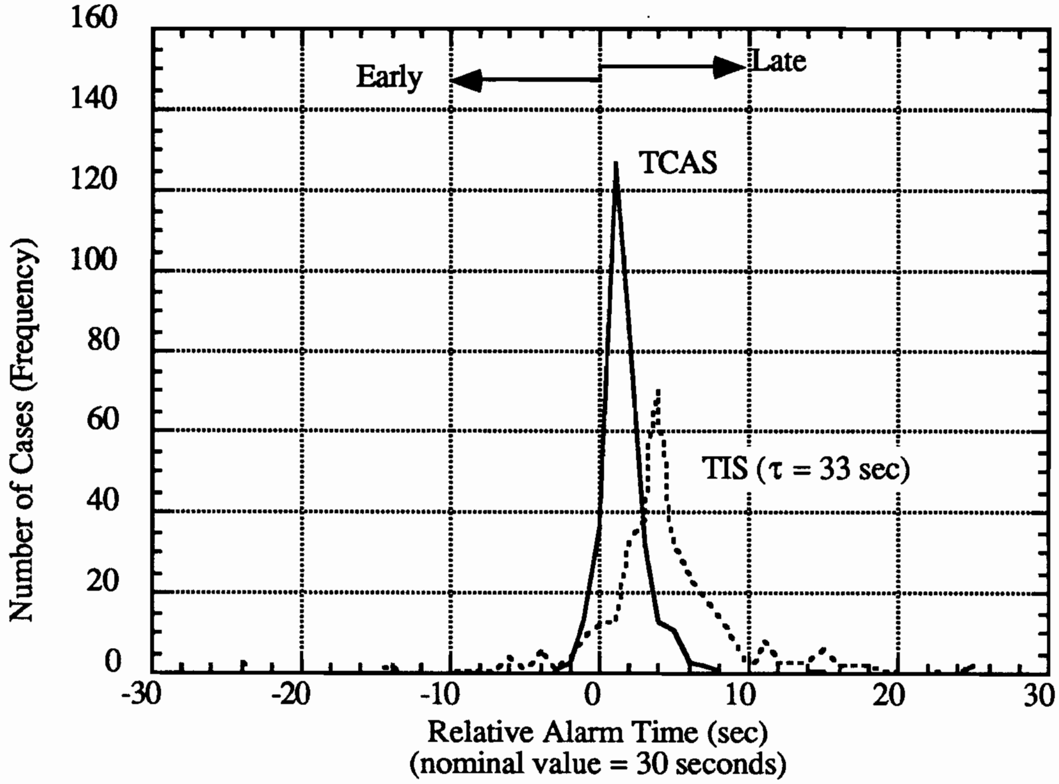

Figure 4. TIS and TCAS alarm times relative to nominal alarm time. TIS τ set to 33 seconds.

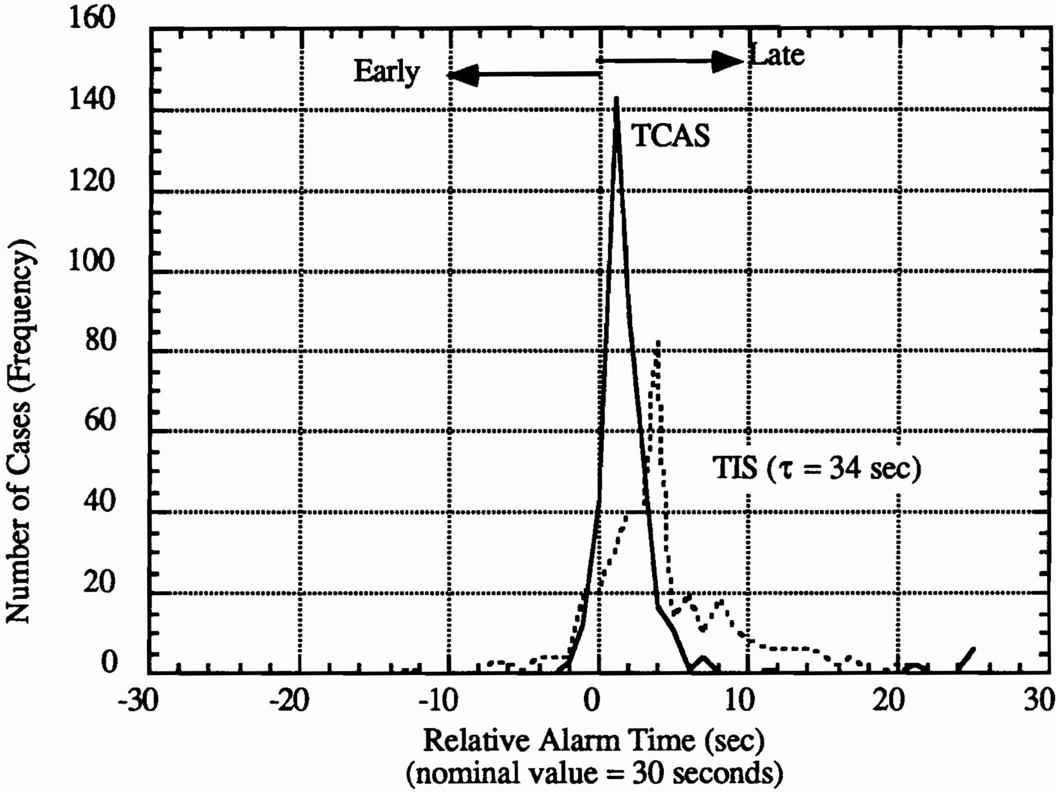

Figure 5. TIS and TCAS alarm times relative to nominal alarm time. TIS τ set to 34 seconds.

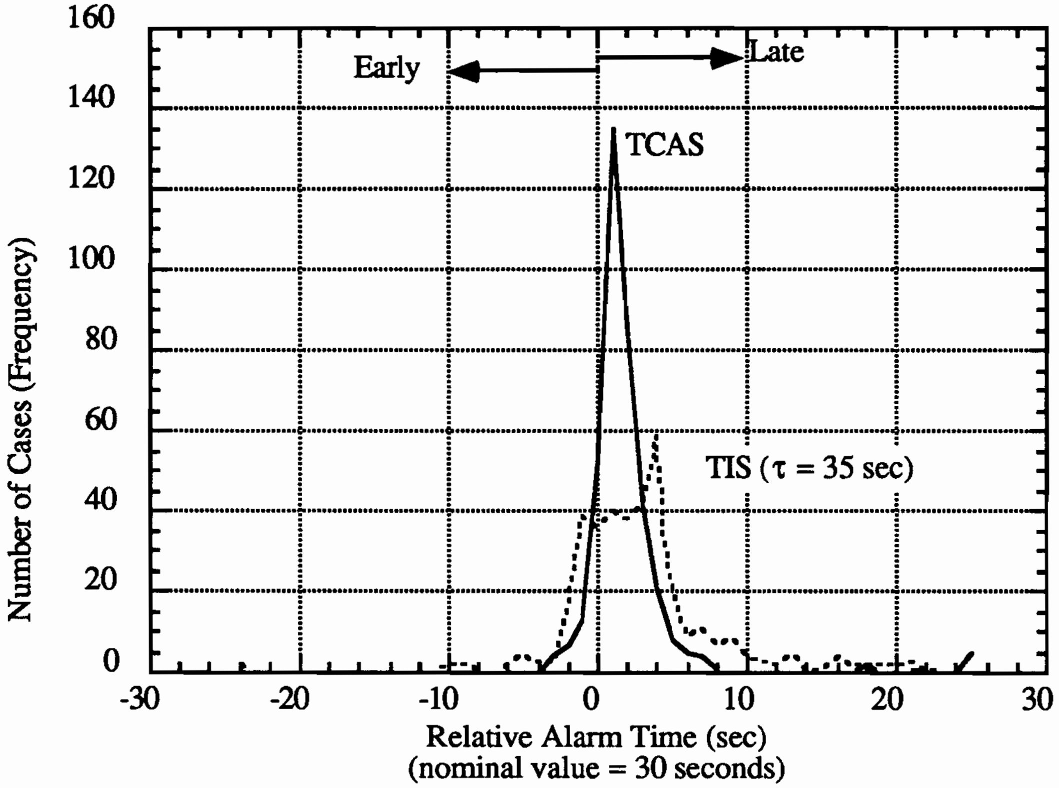

Figure 6. TIS and TCAS alarm times relative to nominal alarm time. TIS τ set to 35 seconds.

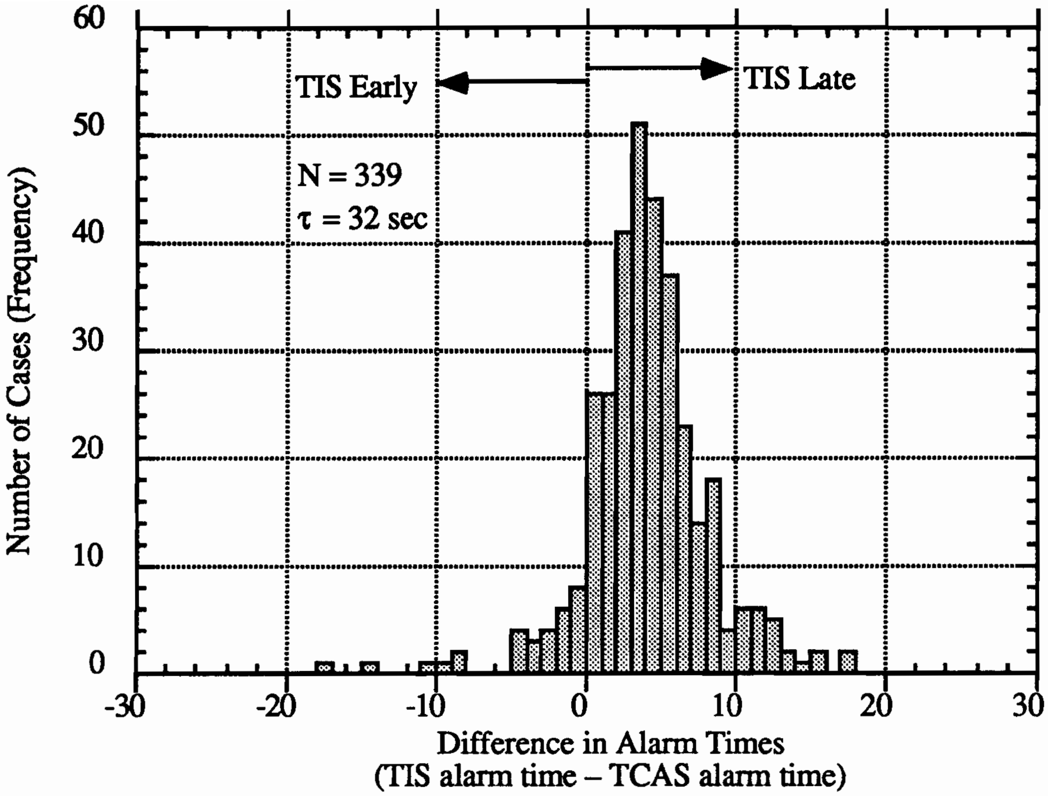

Figure 7. Distribution of alarm-time differences with TIS τ set to 32 seconds.

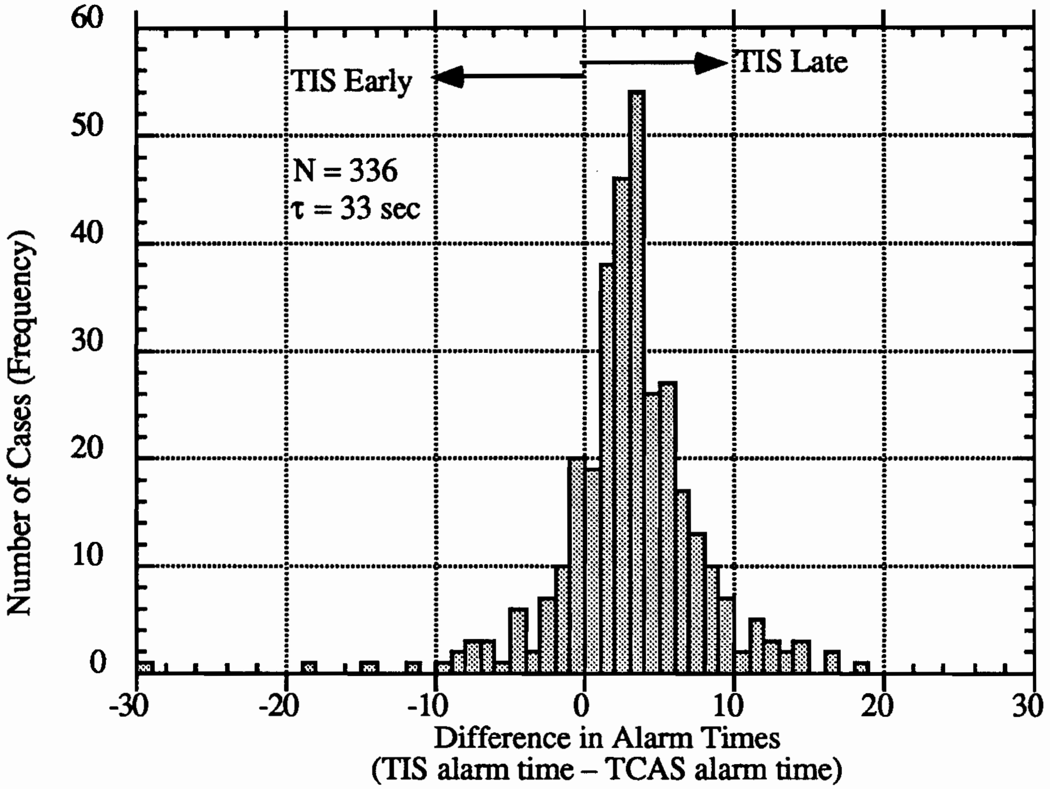

Figure 8. Distribution of alarm-time differences with TIS τ set to 33 seconds.

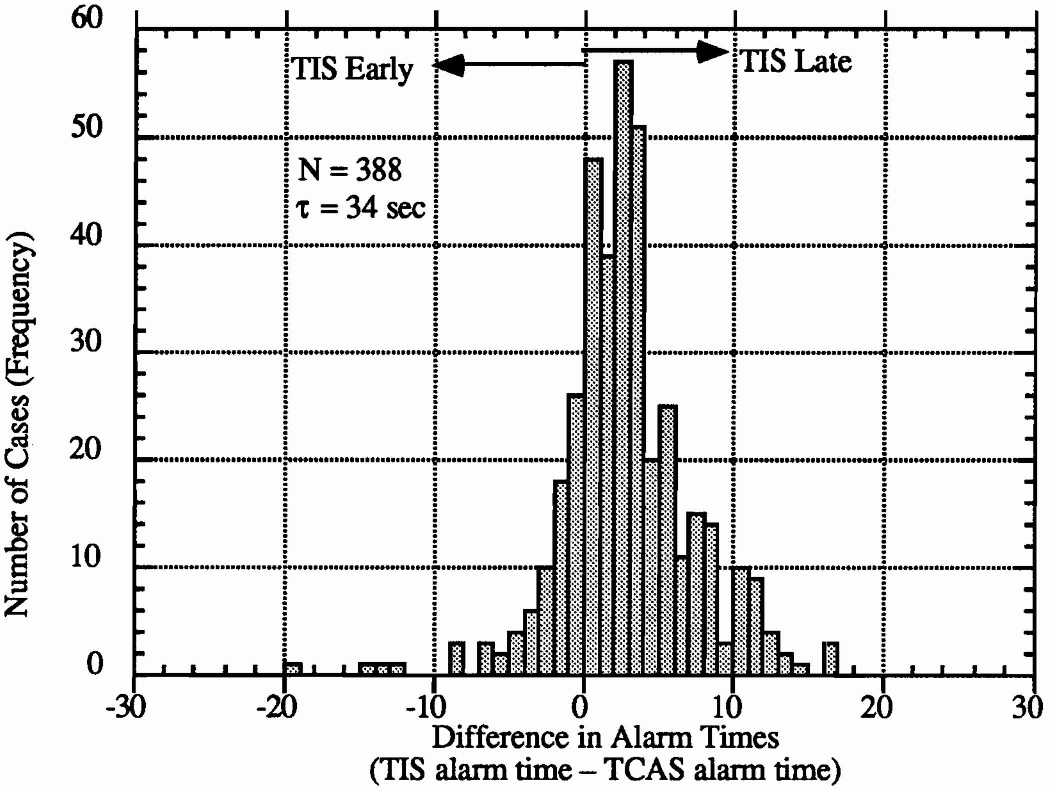

Figure 9. Distribution of alarm-time differences with TIS τ set to 34 seconds.

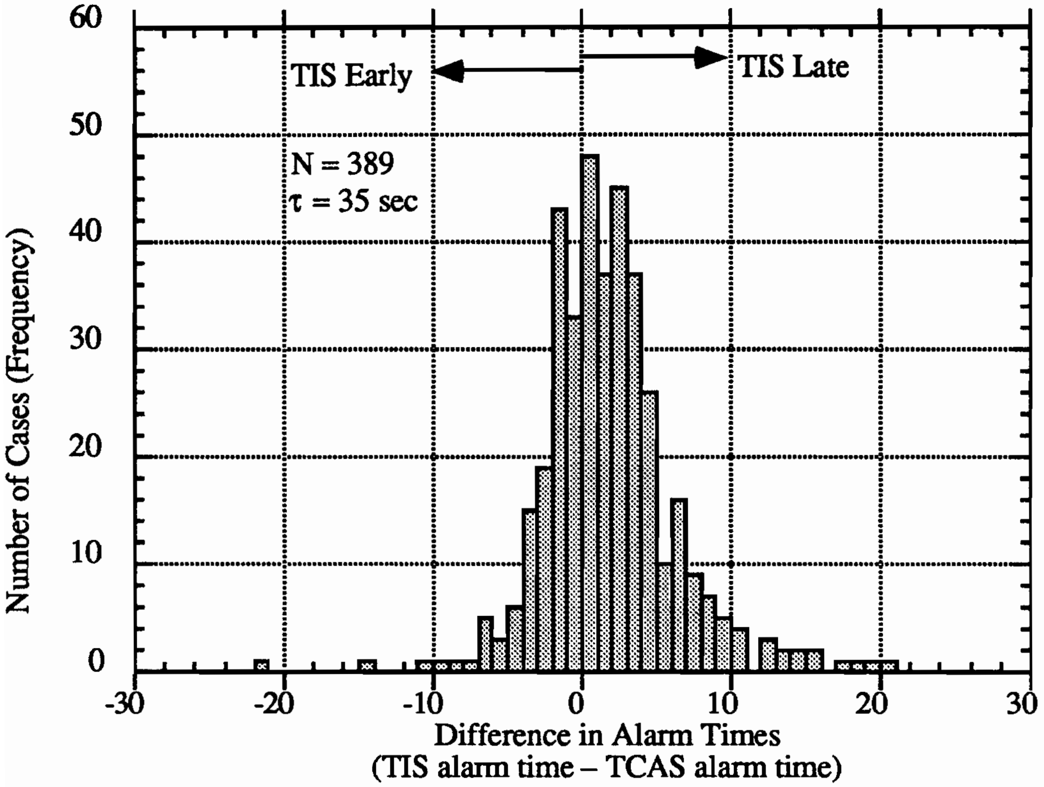

Figure 10. Distribution of alarm-time differences with TIS τ set to 35 seconds.

5. SUMMARY AND CONCLUSIONS

The purpose of this report was to compare the performance of TIS against that of TCAS equipment, specifically, TCAS I. Both systems provide traffic alerting to aid the pilot in visual acquisition. In addition, they assess the degree of threat posed by nearby traffic aircraft. Also, both TCAS I and TIS function automatically; no additional workload is imposed upon the air traffic controller. In terms of aiding in visual acquisition, both systems were shown to result in significantly improved pilot performance. On the basis of Andrews' model of visual acquisition, neither system is expected to outperform the other in terms of traffic alerting. In terms of threat-assessment, the accuracy of TIS is slightly less than that of TCAS equipment (94% correct assessments for TIS versus 98% for TCAS I). Both systems are highly accurate overall. Even if TIS or TCAS failed to declare a threat, the traffic aircraft would still be shown to the pilot as a proximity alert on the cockpit display. If visual acquisition occurs early in the process, as planned, the accuracy of electronic threat assessment is less critical because the pilot can judge the threat independently. On the whole, TIS has been shown to be a reliable and effective means of aiding the pilot in visual acquisition, which is the first and most critical step of collision avoidance.

APPENDIX A: TIS ALPHA-BETA TRACKER PARAMETERS

The TIS alpha-beta tracker parameters are given in Table A.1 below. The tracker is described more fully in McFarland's reports [10, 11].

Table A.1 TIS tracker parameters.

Firmness	Alpha	Beta
1	1.000	0.000
2	1.000	1.000
3	1.000	1.000
4	0.833	0.700
5	0.700	0.409
6	0.600	0.270
7	0.524	0.192
8	0.464	0.144
9	0.417	0.112
10	0.400	0.100

APPENDIX B: RAW SIMULATION RESULTS

The classification of threat assessments is presented in Table B-1. Data from individual runs are given in terms of this taxonomy in Tables B-2 through B-13. In addition, two other statistics are provided: hit rate and false alarm rate. These statistics are defined as follows:

$$\text{hit rate} = \text{hits} / (\text{hits} + \text{misses}) \qquad \text{(Eq. B.1)}$$

$$\text{false alarm rate} = \text{false alarms} / (\text{false alarms} + \text{correct rejections}) \qquad \text{(Eq. B.2)}$$

In the first ten simulation runs (Tables B-2 through B-11), 1000 encounters were run. Of these, the first six runs (in which R_{min} was varied) were conducted with 100 time steps and the last four runs (in which the value of τ was varied) were run with 150 time steps (where each time step equals 1 second). The value of the time-step parameter influences only the number of "true" threat trials, which are called "signals." The number of signals ($N_{signals}$) equals the sum of hits and misses. The larger the value of the time-step parameter, the longer the simulation is run for that encounter, so, the greater the chance of a true threat situation. Hence, $N_{signals}$ is larger for the last four runs than for the first six runs, even though all the runs were of 1000 encounters total.

The final two runs (Tables B-12 and B-13) each contain data from 500 simulated encounters. These data were collected in order to assess the effect of the range of the two aircraft (from the Mode S sensor) on the accuracy of the TIS threat-assessment algorithms. In one case (Table B-12), both aircraft were required to be "close" to the beacon (i.e., at a distance of 1–20 nm from the beacon). In the other (Table B-13), the aircraft were "far" away (i.e., at a distance of 80–100 nm from the beacon).

Table B-1. Format of results.

	Declaration: Threat	Declaration: Nonthreat
"True" threat	Hit	Miss
"True" nonthreat	False Alarm	Correct Rejection

Table B-2. $R_{min} = 0.3$ nm. $\tau = 34$ seconds. Time steps = 100 $N_{signals} = 357$

(a)

	TIS Declaration: Threat	TIS Declaration: Nonthreat	TCAS Declaration: Threat	TCAS Declaration: Nonthreat
"True" threat	329	28	350	7
"True" nonthreat	52	591	17	626

(b)

	TIS	TCAS
Hit Rate	0.922	0.980
False Alarm Rate	0.081	0.026

Table B-3. R_{min} = 0.4 nm. τ = 34 seconds. Time steps = 100 $N_{signals}$ = 360

(a)

	TIS Declaration		TCAS Declaration	
	Threat	Nonthreat	Threat	Nonthreat
"True" threat	340	20	359	1
"True" nonthreat	49	591	15	625

(b)

	TIS	TCAS
Hit Rate	0.944	0.997
False Alarm Rate	0.077	0.023

Table B-4. R_{min} = 0.5 nm. τ = 34 seconds. Time steps = 100 $N_{signals}$ = 380

(a)

	TIS Declaration		TCAS Declaration	
	Threat	Nonthreat	Threat	Nonthreat
"True" threat	367	13	377	3
"True" nonthreat	56	564	18	602

(b)

	TIS	TCAS
Hit Rate	0.966	0.992
False Alarm Rate	0.090	0.029

Table B-5. R_{min} = 0.6 nm. τ = 34 seconds. Time steps = 100 $N_{signals}$ = 366

(a)

	TIS Declaration		TCAS Declaration	
	Threat	Nonthreat	Threat	Nonthreat
"True" threat	350	16	362	4
"True" nonthreat	61	573	11	623

(b)

	TIS	TCAS
Hit Rate	0.956	0.989
False Alarm Rate	0.096	0.017

Table B-6. R_{min} = 0.7 nm. τ = 34 seconds. Time steps = 100 $N_{signals}$ = 364

(a)

	TIS Declaration		TCAS Declaration	
	Threat	Nonthreat	Threat	Nonthreat
"True" threat	355	9	361	3
"True" nonthreat	72	564	12	624

(b)

	TIS	TCAS
Hit Rate	0.975	0.992
False Alarm Rate	0.113	0.019

Table B-7. R_{min} = 0.8 nm. τ = 34 seconds. Time steps = 100 $N_{signals}$ = 366

	TIS Declaration		TCAS Declaration	
	Threat	Nonthreat	Threat	Nonthreat
"True" threat	358	8	356	10
"True" nonthreat	98	536	13	621

(b)

	TIS	TCAS
Hit Rate	0.978	0.973
False Alarm Rate	0.155	0.021

Table B-8. R_{min} = 0.5 nm. τ = 32 seconds. Time steps = 150 $N_{signals}$ = 353

(a)

	TIS Declaration		TCAS Declaration	
	Threat	Nonthreat	Threat	Nonthreat
"True" threat	338	15	348	5
"True" nonthreat	39	608	18	629

(b)

	TIS	TCAS
Hit Rate	0.958	0.986
False Alarm Rate	0.060	0.028

Table B-9. R_{min} = 0.5 nm. τ = 33 seconds. Time steps = 150 $N_{signals}$ = 400

(a)

	TIS Declaration		TCAS Declaration	
	Threat	Nonthreat	Threat	Nonthreat
"True" threat	391	9	395	5
"True" nonthreat	66	534	13	587

(b)

	TIS	TCAS
Hit Rate	0.978	0.988
False Alarm Rate	0.110	0.022

Table B-10. R_{min} = 0.5 nm. τ = 34 seconds. Time steps = 150 $N_{signals}$ = 398

(a)

	TIS Declaration		TCAS Declaration	
	Threat	Nonthreat	Threat	Nonthreat
"True" threat	389	9	395	3
"True" nonthreat	49	553	11	591

(b)

	TIS	TCAS
Hit Rate	0.977	0.992
False Alarm Rate	0.081	0.018

Table B-11. R_{min} = 0.5 nm. τ = 35 seconds. Time steps = 150 $N_{signals}$ = 353

(a)

	TIS Declaration		TCAS Declaration	
	Threat	Nonthreat	Threat	Nonthreat
"True" threat	343	10	345	8
"True" nonthreat	43	604	18	629

(b)

	TIS	TCAS
Hit Rate	0.972	0.977
False Alarm Rate	0.066	0.028

Table B-12. 500 Encounters. R_{min} = 0.5 nm. τ = 34 seconds. Time steps = 100. Range of aircraft to Mode S sensor: 1–20 nm

	TIS Declaration		TCAS Declaration	
	Threat	Nonthreat	Threat	Nonthreat
"True" threat	179	4	178	5
"True" nonthreat	27	290	11	306

(b)

	TIS	TCAS
Hit Rate	0.978	0.973
False Alarm Rate	0.085	0.035

Table B-13. 500 Encounters. R_{min} = 0.5 nm. τ = 34 seconds. Time steps = 100. Range of aircraft to Mode S sensor: 80–100 nm

(a)

	TIS Declaration		TCAS Declaration	
	Threat	Nonthreat	Threat	Nonthreat
"True" threat	188	8	194	2
"True" nonthreat	24	280	3	301

(b)

	TIS	TCAS
Hit Rate	0.959	0.990
False Alarm Rate	0.079	0.010

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