DOT-FAA-AFS-420-83

Flight Procedure Standards Branch
Flight Technologies and Procedures Division
Flight Standards Service

COMPARATIVE STUDY OF AIRBORNE INFORMATION FOR LATERAL SPACING (AILS) SYSTEM WITH PRECISION RUNWAY MONITOR (PRM) SYSTEM

Dr. David N. Lankford
Gerry McCartor
Dr. James Yates, DataCom
Shahar Ladecky, DataCom
Donna Templeton, Editor

U.S. Department of Transportation
Federal Aviation Administration
Mike Monroney Aeronautical Center
Oklahoma City, OK 73125

April 2000

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents or use thereof.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.

DOT-FAA-AFS-420-83

Federal Aviation Administration
Flight Procedure Standards Branch
Mike Monroney Aeronautical Center
Oklahoma City, OK 73125

A COMPARATIVE STUDY OF AIRBORNE INFORMATION FOR LATERAL SPACING (AILS) SYSTEM WITH PRECISION RUNWAY MONITOR (PRM) SYSTEM

Reviewed by:

Donald P. Pate 4/25/00

Donald P. Pate Date
Manager, Flight Procedure
Standards Branch

Released by:

Robert A. Wright 5/1/00

Robert A. Wright Date
Manager, Flight Technologies and
Procedures Division

April 2000

Final Report

Technical Report Documentation Page

1. Report No. DOT-FAA-AFS-420-83	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Comparative Study of Airborne Information for Lateral Spacing (AILS) System with Precision Runway Monitor (PRM) System		5. Report Date April 2000
6. Author(s) Dr. David N. Lankford/Gerry McCartor Dr. James Yates/Shahar Ladecky		7. Performing Organization Code
8. Performing Organization Name and Address Federal Aviation Administration Standards Development Branch P.O. Box 25082, Oklahoma City, OK 73125		9. Type of Report and Period Covered Final Report
10. Sponsoring Agency Name and Address Federal Aviation Administration Standards Development Branch P.O. Box 25082, Oklahoma City, OK 73125		
11. Supplementary Notes		
12. Abstract		

The Precision Runway Monitor (PRM) system, developed by the FAA for precision monitoring of Multiple Parallel Approaches using the Instrument Landing System (ILS), is a ground based system and provides the approach controller with a high fidelity radar view of aircraft performing independent parallel ILS approaches. An approach controller monitors landing traffic and if a blunder is detected relays instructions for an evasion maneuver to the affected aircraft. The Airborne Information for Lateral Spacing (AILS) system, under development by NASA, is an airborne system, requiring a precision navigational approach system such as the Global Positioning System (GPS) augmented by either the Wide Area Augmentation System (WAAS) or the Local Area Augmentation System (LAAS), as well as the Automatic dependent Surveillance-Broadcast (ADS-B) system. Each aircraft transmits its position and the positions are relayed to all aircraft performing the parallel approach via ADS-B. A cockpit display is used to warn the pilot of an aircraft performing a parallel instrument approach of a blunder by an adjacent aircraft. Thus, AILS is an airborne system and eliminates one human, the air traffic controller, with his or her delay. The Airspace Simulation and Analysis for TERPS (ASAT) system was used to perform a comparison of the performance of PRM and AILS. The primary concern is whether the AILS system can provide a level of safety equivalent to that of PRM. If two aircraft approach within 500 feet then a test criterion violation (TCV) is said to occur. The target level of safety (TLS) afforded by the PRM system is equivalent to one accident per 25 million approaches. This level of safety is equivalent to a 6.8% TCV rate. Therefore, in order to meet the target level of safety set for PRM, the AILS TCV rate must not exceed 6.8%. It was found that under certain conditions of warning radius and alert time, AILS met the TLS. However, distributions of pilot response time to the AILS display and AILS and ADS-B latencies were not available. Therefore, the results should be considered preliminary.

13. Key Words	14. Distribution Statement
AILS PRM ASAT	Controlled by AFS-420
15. Security Classification of This Report Unclassified	16. Security Classification of This Page Unclassified

EXECUTIVE SUMMARY

The Precision Runway Monitor (PRM) system was developed by the Federal Aviation Administration (FAA) for precision monitoring of Multiple Parallel Approaches (MPAP) using the Instrument Landing System (ILS) for navigation. PRM is a ground-based system and provides the approach controller a high fidelity radar view of aircraft performing independent parallel ILS approaches. The PRM requires two people for its operation, a controller and a pilot. Delays due to two people, as well as system delays, are inherent in the system. The Airborne Information for Lateral Spacing (AILS) system, under development by NASA, is an airborne system. It requires a precision navigational approach system such as the Global Positioning System (GPS) augmented by either the Wide Area Augmentation System (WAAS) or the Local Area Augmentation System (LAAS), as well as the Automatic Dependent Surveillance-Broadcast (ADS-B) system. Each aircraft transmits its position and the positions are relayed to all aircraft performing the parallel approach via ADS-B. Thus, AILS eliminates one human, the air traffic controller, with his or her delay. However, system delays are not eliminated and, at the time of writing this report, the built-in delays or latencies, of AILS and ADS-B are unknown.

The purpose of this paper is to compare the level of safety of AILS to PRM. Since PRM is certified for parallel approaches separated by at least 3,400 feet, the comparison was made for parallel approaches separated by 3,400 feet.

The Flight Procedure Standards Branch (AFS-420) computer simulation system, the Airspace Simulation and Analysis for TERPS (ASAT) system, was used to perform the comparison. Probability distributions of aircraft dynamics and pilot response time were used as input. The aircraft dynamics distributions were derived from previous real-time simulations. Pilot response time distributions for AILS were not available so three different distributions were used as input. The first distribution was the constant value, 2.5 seconds. For this distribution, the pilot reaction time was always 2.5 seconds. The second distribution was derived from a study of a TCAS display. The mean of this distribution is 5.57 seconds. The third probability distribution of pilot reaction time came from a PRM real-time simulation. The median of this distribution is 5.08 seconds.

AILS uses two critical parameters to determine whether the pilot should receive an alert warning of an adjacent aircraft blunder. The first parameter is R, the radius of a circle centered at the center of gravity of the evading aircraft. The second parameter is T, the maximum warning time. For each pilot response time distribution, a matrix of radii R and time T was ran to determine the TCV rate for each combination of radius R and time T. The target level of safety developed for PRM was used to evaluate the level of safety of AILS. For PRM, the target level of safety was 1 accident per 25,000,000 dual approaches. This was converted to an acceptable TCV rate. The acceptable TCV rate was found to be 6.8%. Therefore, if the TCV rate for a given combination of R and T was less than 6.8%, the target level of safety was met. If the TCV rate exceeded 6.8%, then the target level of safety was not met.

For each probability distribution of pilot response time, there were several combinations of R and T which met the target level of safety. The smallest radius R was R = 500 feet, but it required that T = 14 seconds. The shortest time was T = 12 seconds, but it required that R = 700

feet. These were both found using the 2.5 second constant probability distribution of pilot response time. The other two distributions required larger radii and longer alert times in order to meet the target level of safety.

The results of this simulation must be tempered by the fact that probability distributions of pilot response time are not yet available. In addition, latencies of ADS-B and AILS are also unknown. Therefore, the results of this simulation should be considered to be preliminary.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLES

FIGURES

A COMPARATIVE STUDY OF AIRBORNE INFORMATION FOR LATERAL SPACING (AILS) SYSTEM WITH PRECISION RUNWAY MONITOR (PRM) SYSTEM

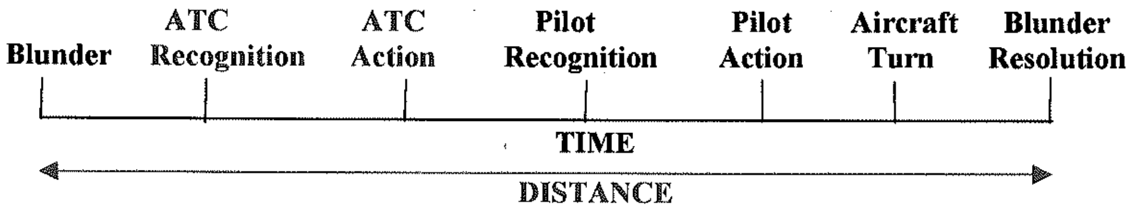
1.0 A DESCRIPTION OF THE AILS AND PRM SYSTEMS

1.1 THE MULTIPLE PARALLEL APPROACH PROGRAM AND PRM

Because of the rapid increase in the volume of commercial air traffic, programs to improve the capacity of the National Airspace System (NAS) have been underway since the early 1980's. One initiative involved the possibility of simultaneous independent instrument approaches to parallel runways. In 1988, the Multiple Parallel Approach Program (MPAP) was initiated to investigate simultaneous Instrument Landing System (ILS) approach operations to various closely spaced dual, triple, and quadruple parallel runway configurations as a means of enhancing capacity. The primary concern of the MPAP was whether simultaneous independent parallel approaches could be safely conducted. Of greatest concern was the possibility that an aircraft, already established on the final approach course, could make an unexpected turn towards another aircraft on an adjacent approach. An unexpected turn is called a blunder.

The MPAP employed a series of real-time and computer simulations to determine that independent multiple parallel approaches can be performed safely to runways spaced as close as 3,400 feet with the aid of a Precision Runway Monitor (PRM). The PRM is a ground-based rapid-update radar alerting system with a high-resolution radar screen. The radar screen depicts a Non Transgression Zone (NTZ) between each pair of adjacent extended parallel runway centerlines. The PRM provides both visual and aural warnings to the controller in the event a blunder should occur. When the PRM computer predicts that a blundering aircraft will enter the NTZ within 10 seconds, the radar target corresponding to the blundering aircraft turns yellow and an aural alert is issued to the controller. When the blundering aircraft enters the NTZ, the radar target turns red. When the red alert is issued the air traffic controller must assess the situation and transmit instructions to the blundering aircraft and, if necessary, evasion instructions to the aircraft on the adjacent approach. The following example depicts the events from Blunder to Blunder Resolution that must occur in a specified length of time to meet the Target Level of Safety (TLS).

PRM/Time Equals Distance*

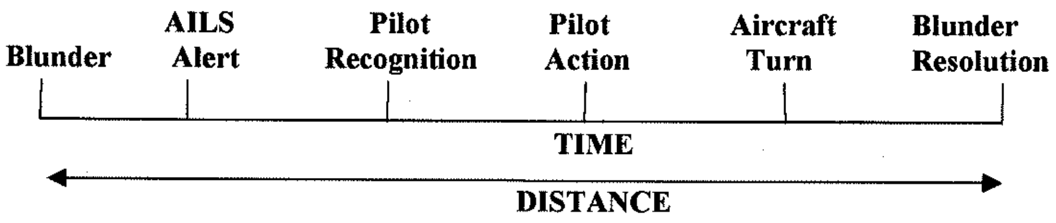


*Using ILS, 1 sec radar update rate, trained ATC and pilots.

1.2 AIRBORNE INFORMATION FOR LATERAL SPACING (AILS)

With the advent of Differential Global Positioning System (DGPS) landing systems and aircraft to aircraft communications via Automatic Dependent Surveillance Broadcast (ADS-B), it has become possible to develop on-board alerting systems for closely spaced parallel approaches. The NASA Langley Research Center has developed alerting algorithms that would utilize DGPS, ADS-B, and a cockpit display to warn the pilot of an aircraft performing a parallel instrument approach of a blunder by an adjacent aircraft. The object of the alerting system is to eliminate the delay of an air traffic controller in detecting and transmitting evasion instructions to the affected aircraft. It was originally envisioned that independent parallel approaches could be conducted with runways spaced as close as 1,500 feet (see Phillips). The AILS system would require DGPS for precise navigation to the runways and ADS-B would allow each aircraft to broadcast its position, as well as other relevant information, throughout the approach procedure. Each aircraft would receive that data and compute the relative position of the other aircraft. Transmitted data would provide the flight crew of each aircraft with an indication of whether traffic is developing a significant deviation from course. The following example depicts the events from Blunder to Blunder Resolution that must occur in a specified length of time to meet the TLS.

AILS/Time Equals Distance*



*Using DGPS, AILS, ADS-B, trained pilots

An on-board computer would use data provided by ADS-B to determine whether or not to issue an alert. The AILS display would display alerts of several levels of urgency depending on the nature of the conflict so that adequate separation would be ensured even if a blundering aircraft is not responsive to alerts.

The AILS algorithm has undergone revision since its inception; however, the algorithm supplied to the Flight Procedure Standards Branch (AFS-420), can be broadly outlined. During parallel operations, if an aircraft begins a turn toward an adjacent approach path, the evading aircraft is modeled as maintaining a constant-velocity approach along the extended runway centerline and glide slope. The blundering aircraft is modeled as potentially following any one of a range of trajectories (see Haissig, et al.). At each positional update, the computer of the evading aircraft would evaluate a series of potential trajectories the blundering aircraft could follow based on its bank angle and airspeed. Each trajectory would incorporate a circular turn followed by a rollout into straight-line flight. The turns would be of sequential length depending on the time, in seconds, allowed for the turn. The first trajectory would have a zero second turn; i.e., a straight line; the second would have a one second turn, the next a 2 second turn, and so on until the maximum time T, called the alert time in this paper, is attained. Thus a fan of trajectories would be generated, starting at the blundering aircraft's current position. If one of the trajectories intersects a circle of radius R horizontal and centered on the evading aircraft, then an alert is issued to the evader. The radius R is called the alert radius in this paper. The alert time T and the alert radius R that were included in the algorithm supplied to AFS-420 were 10 seconds and 500 feet, respectively. The algorithm supplied was two-dimensional and did not include a provision for the altitudes of the two aircraft.

Since the completion of the research required for this simulation, an improved version of AILS has been published (see Samanant, et al.). The improved version features an elliptically shaped protected space in the horizontal plane. The protection ellipse is specified by downrange and cross-range parameters which represent the major and minor axes of the ellipse, respectively. In the vertical plane, the protected region is a specified linear distance above and below the aircraft. An evaluation of this new algorithm will be conducted by AFS-420.

2.0 RISK ASSESSMENT OF MULTIPLE PARALLEL APPROACHES

2.1 TARGET LEVEL OF SAFETY

In order to evaluate the risk that parallel operations entailed, a TLS for parallel approaches was developed by the MPAP. The most recent accident data was examined, along with departure rates, to determine the accident rate during ILS approaches. This rate was used to determine the rate that accidents caused by blunders could be allowed to occur and not increase the current overall ILS approach accident rate. The TLS was found to be 4×10^{-8}, or 1 accident per 25 million approaches.

2.2 AT-RISK BLUNDERS

During the MPAP simulations, blunders were initiated toward an aircraft on an adjacent approach, called the evading aircraft, that involved a standard-rate turn of the blundering aircraft to a thirty degree heading change from the approach heading. In most cases, the blundering aircraft were non-responding; i.e., the pilot of the blundering aircraft did not respond to instructions from the controller to return to the localizer, but continued its flight toward the adjacent aircraft. The evading aircraft was instructed to perform a climbing turn to a 90-degree heading change from the approach heading. It was found that blunders of 20 degrees or less posed an insignificant risk of collision. A 30-degree, non-responding blunder was called a Worst Case Blunder (WCB).

In each case, the smallest separation distance of the two aircraft, called the closest point of approach (CPA), was recorded. The CPA was the slant line distance between the centers of gravity of the two aircraft. If the CPA was less than 500 feet, a Test Criterion Violation (TCV) was said to have occurred. Although in reality, the occurrence of a TCV does not guarantee that a collision will occur, a TCV was treated as a collision. It was found that for each blunder, a risk window; i.e., an alignment window, existed such that if aircraft were not aligned in the risk window, then a TCV could not occur. Therefore, in order to stress the system, blunders were scripted so that the aircraft on the adjacent approach were At-Risk; i.e., the aircraft were aligned so that if either the controller or pilot of the evading aircraft did not react, then a TCV would occur.

2.3 MAXIMUM ALLOWABLE TCV RATE

A collision can occur only if a TCV occurs while the evading aircraft is at-risk during a worst case blunder. If the event "TCV" is denoted by *T*, the event "At-Risk" is denoted by *A*, the event "Worst Case Blunder" is denoted by *W*, the event "Blunder" is denoted by *B*, and the symbol $\cap$ is used to denote "and", then the probability, or risk, of a collision can be denoted mathematically as $P(T \cap A \cap W \cap B)$. Since the TLS was found to be 4×10^{-8}, it follows that for a procedure to be acceptable the following inequality must be true.

$$4 \times 10^{-8} \geq P(T \cap A \cap W \cap B). \quad (1)$$

If the symbol "$|$" denotes the word "given", the probability of collision, $P(T \cap A \cap W \cap B)$, can be described by the equation:

$$P(T \cap A \cap W \cap B) = P(T|A \cap W \cap B)P(A|W \cap B)P(W|B)P(B) \quad (2)$$

The real-time and computer simulations performed by the MPAP were used to estimate $P(T|A \cap W \cap B)$; i.e., the probability a TCV occurs given that a worst case, at-risk blunder occurred. Two other factors, $P(A|W \cap B)$ and $P(W|B)$ could also be estimated. But the fourth factor, $P(B)$, the probability of a thirty degree blunder, was unknown. However, by substituting 4×10^{-8} for $P(T \cap A \cap W \cap B)$ in equation (2), equation (2) could be solved for P(*B*). The result is the following equation:

$$P(B) = 4 \times 10^{-8} /(P(T|A \cap W \cap B)P(A|W \cap B)P(W|B)) \quad (3)$$

By substituting $P(T|A \cap W \cap B)$, from the simulation, and $P(A|W \cap B)$ and $P(W|B)$ into equation (3), P(*B*) could be calculated. However, P(*B*) did not represent the operational blunder rate, instead P(*B*) represented the maximum blunder rate that the system could tolerate and still meet the TLS. Even though the operational blunder rate was unknown, it was known to be quite small. Therefore, if P(*B*) was large, it was obvious that P(*B*) was larger than the actual operational blunder rate, which meant that the simulated operation met the TLS. The value of P(*B*) that was adopted by the MPAP was developed in a 1991 report (3). It was determined in that report that P(*B*) = 1/2000, or 1 blunder per 2000 dual approach pairs, was an acceptable maximum blunder rate. This acceptable maximum blunder rate was then converted into an acceptable TCV rate. The maximum acceptable TCV rate for dual simultaneous independent approaches was found to be 6.8%. If a simulated dual approach operation could be shown to have a TCV rate less than or equal to 6.8%, then the operation met the TLS.

3.0 COMPARISON OF AILS AND PRM

3.1 BACKGROUND AND OVERVIEW

AFS-420 was tasked to compare NASA's Airborne Information for Lateral Separation (AILS) system with FAA's Precision Runway Monitor (PRM) system. In August 1999, NASA supplied a then current version of AILS. This report contains numerical results of several Monte-Carlo simulations of that version of AILS using the Airspace Simulation and Analysis for TERPS (ASAT) computer simulation system. These results are used to quantify the anticipated level of safety of the AILS system when analyzed using the same criteria that were applied to PRM.

PRM is suitable for parallel approaches that are spaced 3,400 feet or more apart. If one of the approaches utilizes a 3-degree localizer offset, then the runways can be spaced as close as 3,000 feet. AILS is intended to be used for runways spaced 3,400 feet like PRM, but is also intended for runways spaced much closer than 3,400 feet. Since the least spacing that is authorized for PRM is 3,400 feet, the systems can only be compared for 3,400 feet spacing. However, it will be of great interest to perform the same type of analysis to test the AILS level of safety for runways spaced less than 3,400 feet.

Both systems, PRM and AILS, require one or more humans for their operation. The PRM system requires two humans, an air traffic controller and a pilot, while AILS requires only a pilot. Therefore, in both cases the human factor is one of the most important components that determine the overall system performance after the system is made operational. Since at least one human is embedded as an integral part of each system, it is necessary to model the human behavior as accurately as possible.

One of the challenges faced in modeling a human for simulation purposes is the variation of human response to the same set of initial conditions. For example: if a pilot were to repeatedly fly the same instrument approach under exactly the same conditions and if the pilot should be instructed to manually perform the same evasion maneuver during each approach, then probability distributions will be generated for each the following parameters:

a. Pilot response time,

b. Maximum bank angle,

c. Maximum bank rate,

d. Indicated air speed just prior to the evasion maneuver,

e. Rate of change of indicated air speed,

f. Maximum rate of climb,

g. Rate of change of rate of climb, and
h. Time difference between initiation of the turn to initiation of the climb.

During actual operations these values will vary between flights, even if the same pilot flies the same approach under the same initial conditions. Therefore, it is not realistic to select fixed values for human related parameters.

AFS-420 has developed a procedure to obtain the distributions that define the human response models for cases such as PRM or AILS. The method relies on data that was obtained from real-time simulations performed with realistic operational scenarios and a realistic environment. In the real-time simulations, FAA qualified, six-degrees-of-freedom simulators, operated by current and qualified airline pilots, were used to obtain data containing pilot response times and the aircraft dynamics listed above. To obtain air traffic controller related data, journeyman air traffic controllers operated radar displays identical to those that were to be used during actual operations. The ASAT system data handling and analysis capabilities were used to analyze the data and develop continuous probability density curves required for use in the simulation.

One source of pilot response time data for inclusion in this simulation comparison was a previous simulation conducted by the MPAP. However, the alert transmission in the MPAP simulation was done by voice radio instead of an electronic display. A second source was an early NASA study of pilot response time to a cockpit display (see Phillips) that found response times were less than two seconds. A third source was a study of a TCAS cockpit alert display system (see Billman) that found the mean response time to be 5.57 seconds with a maximum response time of 10 seconds. Because of the lack of reliable pilot response time data to the AILS cockpit alert display, the study was performed using these three different pilot response time distributions, namely:

a. Constant 2.5 seconds, representing the NASA study,

b. The TCAS pilot response time distribution due to Billman, and

c. The pilot response time distribution developed from an MPAP simulation of approaches using PRM.

Every electronic system has an inherent delay or latency; however, because of a lack of data or specifications, the latencies of ADS-B and AILS were not available. Therefore, the system latencies for both ADS-B and AILS were set equal to zero. For PRM, the average system latency was 0.5 seconds. Additionally, it was the purpose of this study to compare the AILS risk of collision to that of PRM so the false alarm rate of AILS was not considered. Since the PRM minimum runway spacing for parallel approaches is 3,400 feet, the runway spacing for the AILS evaluation was set at 3,400 feet.

3.2 TEST PROCEDURE

The ASAT simulation system was used to compare the AILS level of safety to the PRM level of safety. The following items describe the various conditions under which the simulation runs were executed:

3.2.1 RUNWAY CONFIGURATION

The configuration of the runways for the simulation was as follows:

a. Parallel runways were spaced 3,400 feet apart,

b. Runways were at sea level, and

c. Runway thresholds were not staggered.

3.2.2 ATMOSPHERIC CONDITIONS

The atmospheric conditions used for the simulation were as follows:

a. Standard atmosphere, and

b. Calm weather (no winds).

3.2.3 OPERATIONAL CONDITIONS

The operational conditions of the simulation were as follows:

a. The aircraft mix consisted of a national fleet average with 10% heavies (such as B747s, MD-11s etc.).

b. Aircraft were flown at their nominal approach speeds.

c. Upon receiving an AILS alert, an evasion maneuver consisting of a 45-degree turn, climb, and acceleration was initiated by the evading aircraft.

d. A TCV was considered to be any case in which the closet point of approach (CPA) of the aircraft was less than 500 feet slant range.

e. All evading aircraft were placed at-risk; i.e., if no evasion maneuver was performed, then the run would result in a TCV.

f. ADS-B had no errors or latency. In every case, ADS-B transmitted the actual adjacent aircraft state, including bank angle with no errors, at intervals as defined in RTCA Document: RTCA SC-186, Doc # RTCA/DO-242.

g. There was no latency in the AILS system. The AILS display was updated instantaneously when an ADS-B transmission was received.

h. Both evading and blundering aircraft were navigating using Global Positioning System (GPS) Wide Area Augmentation (WAAS). Because of the close proximity of the two aircraft, the position errors after WAAS corrections were assumed the same for both aircraft.

3.2.4 PROBABILITY DISTRIBUTIONS

The following probability distributions derived from previous simulations were used in the simulation:

a. Aircraft types,

b. Indicated airspeed,

c. Bank angle,

d. Bank rate,

e. Rate of climb,

f. Rate of change of rate of climb,

g. Acceleration, and

h. Pilot response time:

(1) Fixed (2.5 Seconds),

(2) TCAS, and

(3) PRM.

A detailed description of the distributions is given in appendix A.

3.2.5 MATRIX OF SENSITIVITY ANALYSIS

-

The AILS algorithm supplied to AFS-420 used an alert time of 10 seconds and an alert radius of 500 feet. However, in order to evaluate the potential level of safety of the AILS algorithm, the study was designed to incorporate a sensitivity analysis of the level of safety by varying two independent parameters, the AILS alert time and the AILS alert radius. The purpose of the analysis was to determine under what combinations of alert radius, R, and alert time, T, AILS will meet the TLS. In this study, the alert time was varied from 10 to 16 seconds with increments of 1 second and the alert radius was varied from 500 to 900 feet with increments of 100 feet. The same sensitivity analysis was performed for each of the three pilot time distributions.

4.0 SIMULATION RESULTS

The results of the simulation are presented in tables 1, 2, and 3. Table 1 depicts the simulation results for the constant, 2.5 second pilot response time distribution. Table 2 depicts the simulation results for the TCAS pilot response time distribution due to Billman. Table 3 depicts the simulation results for the PRM pilot response time distribution. The entries in each table represent the TCV rate that was observed for the given alert radius R and alert time T. The entries are color-coded. The red entries are those that exceeded the TLS; i.e., the TCV rate exceeded 6.8%. The green entries are those that were less than or equal to the TLS.

In table 1, the pilot response time was a constant 2.5 seconds. When the alert time reached 12 seconds and the alert radius reached 700 feet, then the TLS was met. When the alert time reached 13 seconds and the alert radius reached 600 feet, then the TLS was met. The TLS was met for each alert radius when the alert time was either 14 or 15 seconds. Charts B-1 and B-2 found in appendix B depict the table 1 entries in graphical form. In each chart, a horizontal line labeled "pass" denotes the 6.8% TLS TCV rate.

Radius (feet)	**ALERT TIME (SECONDS)**					
	10	11	12	13	14	15
500	73.40	48.61	23.63	8.73	2.53	0.69
600	59.00	33.01	13.03	4.13	1.03	0.35
700	42.42	20.08	6.76	2.07	0.59	0.23
800	28.01	11.44	3.52	1.10	0.31	0.17

Table 1: TCV RATES FOR 2.5 SECOND CONSTANT PILOT RESPONSE TIME

Table 2 depicts the results of the simulation using the TCAS distribution of pilot response times. The TLS was first met when the alert time reached 14 seconds with a 900 feet alert radius. The TLS was also met with an alert time of 15 seconds and an alert radius of at least 700 feet. The TLS was met with an alert time of 16 seconds with each alert radius tested. Charts B-3 and B-4, found in appendix B, depict the table 2 entries in graphical form. In each chart, a horizontal line labeled "pass" denotes the 6.8% TLS TCV rate.

Radius (feet)	ALERT TIME (SECONDS)						
	10	11	12	13	14	15	16
500	92.60	80.80	70.60	51.40	31.36	12.84	6.13
600	84.80	72.50	58.50	41.05	20.44	8.56	4.44
700	80.20	64.90	51.10	28.45	12.18	6.00	3.70
800	72.20	56.90	37.70	18.90	9.60	5.80	2.78
900	65.00	50.20	27.90	13.50	5.93	3.54	1.86

Table 2: TCV RATES FOR TCAS DISTRIBUTION OF PILOT RESPONSE TIMES

Table 3 depicts the results of the simulation using the PRM distribution of pilot response times. The TLS was first met when the alert time reached 15 seconds with an alert radius of 700 feet. The TLS was also met when the alert time was 16 seconds with an alert radius of 600 feet. Charts B-5 and B-6, found in appendix B, depict the table 3 entries in graphical form. In each chart, a horizontal line labeled "pass" denotes the 6.8% TLS TCV rate.

Radius (feet)	ALERT TIME (SECONDS)						
	10	11	12	13	14	15	16
500	94.10	84.00	69.50	48.90	25.60	11.60	6.97
600	90.70	76.90	59.30	32.30	16.70	8.50	5.66
700	80.80	64.20	43.00	25.40	11.70	6.37	4.27
800	74.50	53.10	33.80	18.90	9.40	5.63	3.72
900	60.30	42.10	23.40	12.65	6.85	4.55	3.15

Table 3: TCV RATES FOR PRM DISTRIBUTION OF PILOT RESPONSE TIMES

5.0 SUMMARY AND CONCLUSIONS

The PRM system was developed by the FAA for precision monitoring of Multiple Parallel ILS Approaches. PRM is a ground based system and provides the approach controller a high fidelity radar view of aircraft performing independent parallel ILS approaches. The PRM requires two people for its operation, a controller and a pilot. Delays due to two people, as well as system delays, are inherent in the system. The AILS system is an airborne system. It requires a precision navigational approach system such as GPS WAAS or LAAS, as well as ADS-B. Each aircraft transmits its position and the positions are relayed to all aircraft performing the parallel approach via ADS-B. Thus, AILS eliminates one human, the air traffic controller, with his or her delay. However, system delays are not eliminated and, at the time of writing this report, the built-in delays or latencies, of AILS and ADS-B are unknown.

The purpose of this paper is to compare the level of safety of AILS to PRM. Since PRM is certified for parallel approaches separated by at least 3,400 feet, the comparison was made for parallel approaches separated by 3,400 feet.

The computer simulation system, the Airspace Simulation and Analysis for TERPS (ASAT) system was used to perform the comparison. Probability distributions of aircraft dynamics and pilot response time were used as input. The aircraft dynamics distributions were derived from previous real-time simulations. Pilot response time distributions for AILS were not available so three different distributions were used as input. The first distribution was the constant value, 2.5 seconds. For this distribution, the pilot reaction time was always 2.5 seconds. The second distribution was derived from a study of a TCAS display. The mean of this distribution is 5.57 seconds. The third probability distribution of pilot reaction time came from a PRM real-time simulation. The median of this distribution is 5.08 seconds.

AILS uses two critical parameters to determine whether the pilot should receive an alert warning of an adjacent aircraft blunder. The first parameter is R, the radius of a circle centered at the center of gravity of the evading aircraft. The second parameter is T, the maximum warning time. For each pilot response time distribution, a matrix of radii R and time T was computed to determine the TCV rate for each combination of radius R and time T. The TLS developed for PRM was used to evaluate the level of safety of AILS. For PRM, the TLS was 1 accident per 25,000,000 dual approaches. This was converted to an acceptable TCV rate. The acceptable TCV rate was found to be 6.8%. Therefore, if the TCV rate for a given combination of R and T was less than 6.8%, the TLS was met. If the TCV rate exceeded 6.8%, then the TLS was not met.

For each probability distribution of pilot response time, there were several combinations of R and T which met the TLS. These combinations are presented in tables 1, 2, and 3. From these tables, it can be concluded that the R value of 500 feet and T value of 10 seconds, as originally used in AILS, are insufficient to meet the TLS for dual runways spaced 3,400 feet apart. The FAA analysis recommends that the R value will need to be in the range of 700 feet and T value in the range of 15 seconds to compare to the TLS used in the PRM program.

The results of this simulation must be tempered by the fact that probability distributions of pilot response time are not yet available. In addition, latencies of ADS-B and AILS are also unknown. Furthermore, the AILS algorithm has been recently revised so that the alert algorithm is elliptical instead of circular. Therefore, the results of this simulation should be considered to be preliminary.

BIBLIOGRAPHY

1. Billman, B., Morgan, T., Windle, J., *Modeling Pilot Response Delays to Beacon Collision Avoidance System Commands*, National Technical Information Service, Springfield, VA, 22161, 1979

2. Flannery, B. P., Press, W. H., Teukolsky, S.A., and Vetterling, W.T., *Numerical Recipes in C*, Cambridge University Press, New York, 1995, pp. 274–283

3. Hahn, G. J., Shapiro, S. S., *Statistical Models in Engineering*, Wiley, New York, 1968, pp. 198-220.

4. Haissig, C. M., Corwin, Bill, Jackson, Mike, "Designing an Airborne Alerting System for Closely Spaced Parallel Approaches", American Institute of Aeronautics and Astronautics, 99-3986.

5. Phillips, E. H., "Langley Developing AILS Multiple Approach Concept", Aviation Week & space Technology, July 1, 1996.

6. *Precision Runway Monitor Demonstration Report*, DOT/FAA/RD-91/5, National Technical Information Service, Springfield, VA, 22161, 1991.

7. Samanant, P., Jackson, M., *Description of the AILS Alerting Algorithm*, NASA Order Number L-10690, NASA Langley Research Center, Version 2.0, Feb. 29, 2000.

8. Waller, M. C., Scanlon, C. H., *Proceedings of the NASA Workshop on Flight Deck Centered Parallel Runway Approaches in Instrument Meteorological Conditions,* NASA Conference Publication 10191, Hampton, VA, 1996.

APPENDIX A

DISTRIBUTIONS AND VALUES USED IN ASAT RUNS

A-1. PROBABILITY DISTRIBUTIONS

The probability distributions used for the simulation of four types, uniform, discrete, normal, Johnson, and ICAO Collision Risk Model.

A-1.1. UNIFORM DISTRIBUTIONS

Central to any computer simulation is the generation of random numbers. A random number generator is a computer program that computes numbers that lie within a specified range (typically 0 to 1) with any one number in the range just as likely as any other. Random numbers that are computed uniformly within a specified range are often called "uniform deviates". Most C language implementations have library routines for generating uniform deviates. However, many if not most, of these implementations are flawed. Therefore, ASAT employs a random number generator developed by L'Ecuyer (see Flannery, et al.). The sequence of uniform deviates produced by this generator passes all known tests of randomness.

A-1.2. DISCRETE DISTRIBUTIONS

The pairing of aircraft for the simulation is also performed in a random fashion. The interval of uniform deviates, $0 \leq y \leq 1$ is divided into subintervals , $y_i \leq y <$, y_{i+1} such that the length of each subinterval corresponds to the proportion of times that a particular aircraft is to be chosen. For example, if a B727 is to be chosen 33% of the time, a subinterval that is 0.33 long is assigned to B727. Then in the simulation, if a random deviate y is chosen that falls in the subinterval assigned to B727, the aircraft chosen for the simulation run is a B727. If a random deviate falls in the subinterval assigned to the B737, then a B737 is selected for the simulation run. This type of distribution is called a discrete distribution.

A-1.3. NORMAL DISTRIBUTIONS

Second only in importance to the generation of uniform random numbers described in A-1.1. is the generation of random deviates from a normal distribution. The Box-Muller method is a simple, but effective, method for generating random deviates from a normal distribution with mean 0 and standard deviation 1. Two random deviates, x_1 and x_2, from a normal distribution with mean 0 and standard deviation 1 can be computed by first finding two uniform deviates, u_1 and u_2. Then compute x_1 and x_2 from the following formulae:

$$\begin{aligned} x_1 &= \sqrt{-2\ln u_1}\cos 2\pi u_2 \\ x_2 &= \sqrt{-2\ln u_1}\sin 2\pi u_2 \end{aligned} \qquad \text{A(1)}$$

If random deviates from a normal distribution with a mean different from 0 and/or a standard deviation different from 1 are needed, then the deviates y_1 and y_2 can be computed from the following formulae:

$$
\begin{aligned}
y_1 &= \mu + \sigma x_1 \\
y_2 &= \mu + \sigma x_2
\end{aligned}
\qquad \text{A(2)}
$$

where μ is the mean of the normal distribution being simulated and σ is its standard deviation.

If random deviates from a truncated normal distribution are required, then there are two numbers a and b, with $a < b$, such that every random deviate y must fall between a and b. The numbers a and b are determined from physical aspects of the data such as minimum and maximum indicated airspeeds or rates of climb. To sample from a truncated normal distribution, a random deviate y is selected from the entire normal distribution. The deviate is checked to see if it lies between a and b. If it lies between a and b, then it is used in the simulation. If it does not lie between a and b, then it is discarded and another random deviate is selected. The process is repeated until a random deviate lying between a and b is found.

A-1.4. JOHNSON DISTRIBUTIONS

The generation of deviates from a Johnson S_B distribution is a three step process. First two uniform deviates must be generated as described in paragraph A1.1. Then the uniform deviates are used to generate two deviates x_1 and x_2 from a normal distribution with mean 0 and standard deviation 1. Then two deviates y_1 and y_2 from a Johnson S_B distribution are computed from the equations:

$$
y_i = \frac{(\varepsilon + \lambda)\exp\left(\frac{x_i - \gamma}{\delta}\right) + \varepsilon}{\left(1 + \exp\left(\frac{x_i - \gamma}{\delta}\right)\right)}, \quad i = 1,2. \qquad \text{A(3)}
$$

A-1.5. COLLISION RISK MODEL DISTRIBUTIONS

The ICAO Collision Risk Model (CRM) includes cumulative probability distributions of lateral and vertical deviations from the glide slope of an ILS approach (see Manual on the Use of the Collision Risk Model (CRM) for ILS Operations). There are distributions for hand flown approaches, flight director approaches, and coupled approaches. These distributions have been incorporated in ASAT in order to randomly position the simulated aircraft relative to a glide slope. The CRM distributions are not defined by equations like a normal distribution or a Johnson distribution. The CRM distributions are in tabular form with separate distributions for lateral deviation from the localizer course and vertical deviations from the glide slope. The table entries are of the form (x_i, y_i), where x_i represents a distance from the localizer course or the glide slope and y_i is the probability that a deviation will exceed that distance. Since the distributions are written as cumulative distributions, random variates can be derived using the method of inversion. A cumulative distribution has the general form $y = F(x)$, where y is the probability that the random variable X will be less than or equal to x. Since $0 \leq y \leq 1$, random deviates x can be generated by first finding the inverse function $x = F^{-1}(y)$. Then random deviates x are computed by computing a uniform random deviate y and substituting y into the equation

$x = F^{-1}(y)$. Since the CRM distributions are in tabular form, when a uniform variate y is generated, a search of the table is performed to find two consecutive points (x_i, y_i) and (x_{i+1}, y_{i+1}), such that, $y_i \leq y <, y_{i+1}$. Then linear interpolation is used to locate x between x_i and x_{i+1} corresponding to y.

The following distributions were used for the Monte-Carlo runs:

A-2.0. SIMULATION PROBABILITY DISTRIBUTION PARAMETERS

A-2.1. PILOT RESPONSE TIME

A-2.1.1. Fixed Value

2.5 Seconds

A-2.1.2. PRM

Type:	Johnson SB
Xi:	0.9772152784e+00
Lambda:	0.6224611455e+08
Delta:	0.1753367537e+01
Gamma:	0.2899054066e+02
Min:	1.90
Max:	13.30

A-2.1.3. TCAS

Normal Bounded

Lower Bound:	1.00 Seconds
Higher Bound:	10.00 Seconds
Mean:	5.57 Seconds
Sigma:	4.80 Seconds

A-2.2. ADS-B

Update period as per RTCA/DO-242 Appendix J, Figure J-36:

Update Period:	0.5 Seconds
Probability:	30%

ADS-B Latency: 0.00 Sec

A-2.3. AILS

Alert Times:

Min:	10.0 Seconds
Max:	16.0 Seconds
Step	1.0 Seconds

Alert Distances

Min	500 Feet
Max:	900 Feet
Step:	100 Feet

AILS Latency: 0.00 Seconds

A-2.4. BANK ANGLE

Type:	Johnson SU
Xi:	0.2790370214e+02
Lambda:	0.5345712321e+01
Delta:	0.1210116524e+01
Gamma:	0.5657027258e-01
Min:	15.0
Max:	30.0

A-2.5. BANK RATE

Type:	Johnson SB	
Xi:	-0.2087380534e+01	
Lambda:	0.5135273947e+02	
Delta:	0.2486335599e+01	
Gamma:	0.4669481170e+01	
Min:	1.5Max:	10.0

A-2.6. RATE OF CHANGE OF RATE OF CLIMB

Type:	Johnson SB
Xi:	-0.9059719786e+02
Lambda:	0.1884613897e+09
Delta:	0.2550175779e+01
Gamma:	0.3490863944e+02
Min:	-100.0
Max:	4000.0

A-2.7. TIME TURN TO CLIMB

Type:	Johnson SB
Xi:	-0.6052752698e+01
Lambda:	0.7986362597e+09
Delta:	0.1597194733e+01
Gamma:	0.2892740641e+02
Min:	-100.0
Max:	100.0

A-2.8. AIRCRAFT TYPES MIX

10% Heavies

APPENDIX B

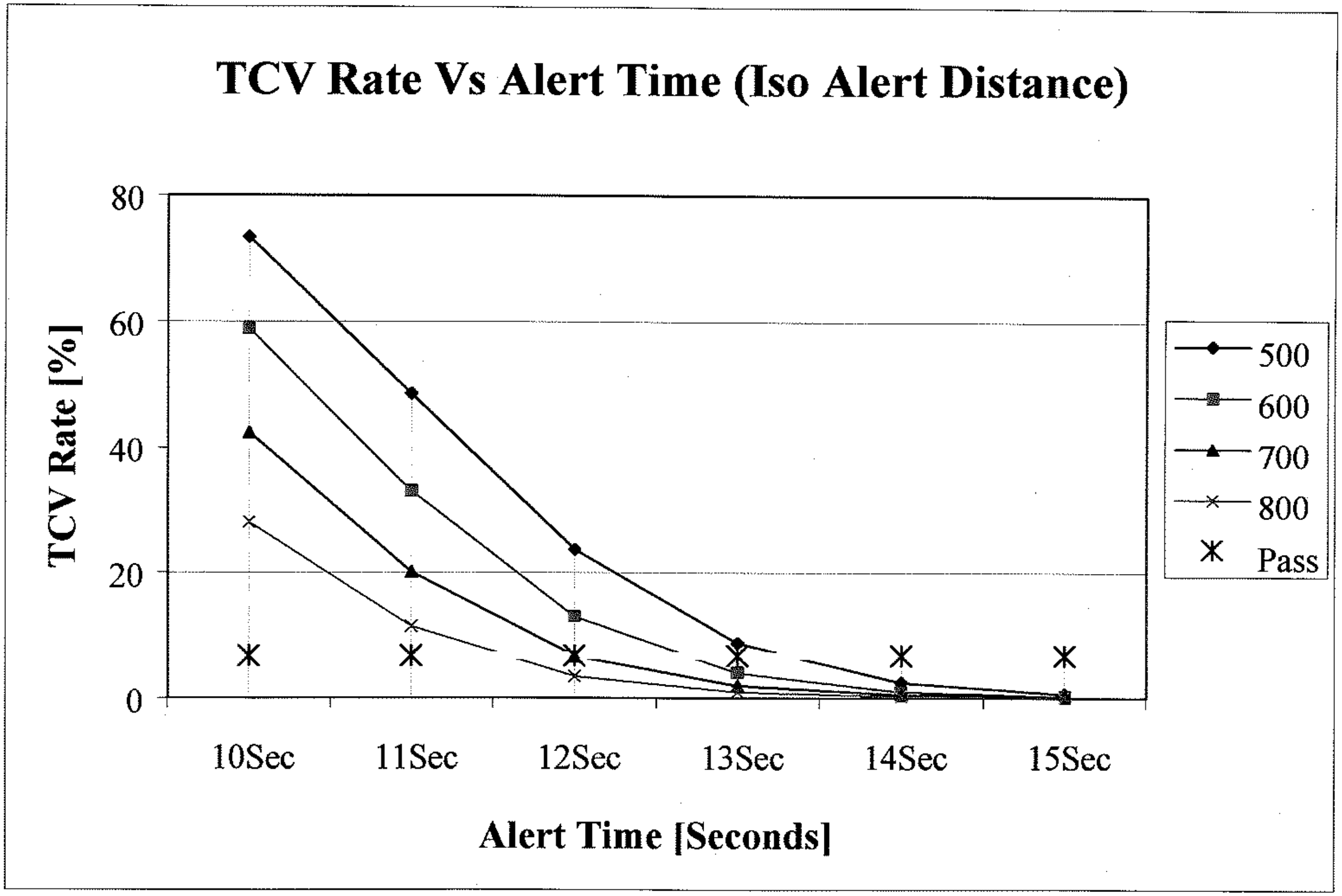


Chart B-1: CONSTANT PILOT RESPONSE TIME: 2.5 SECONDS

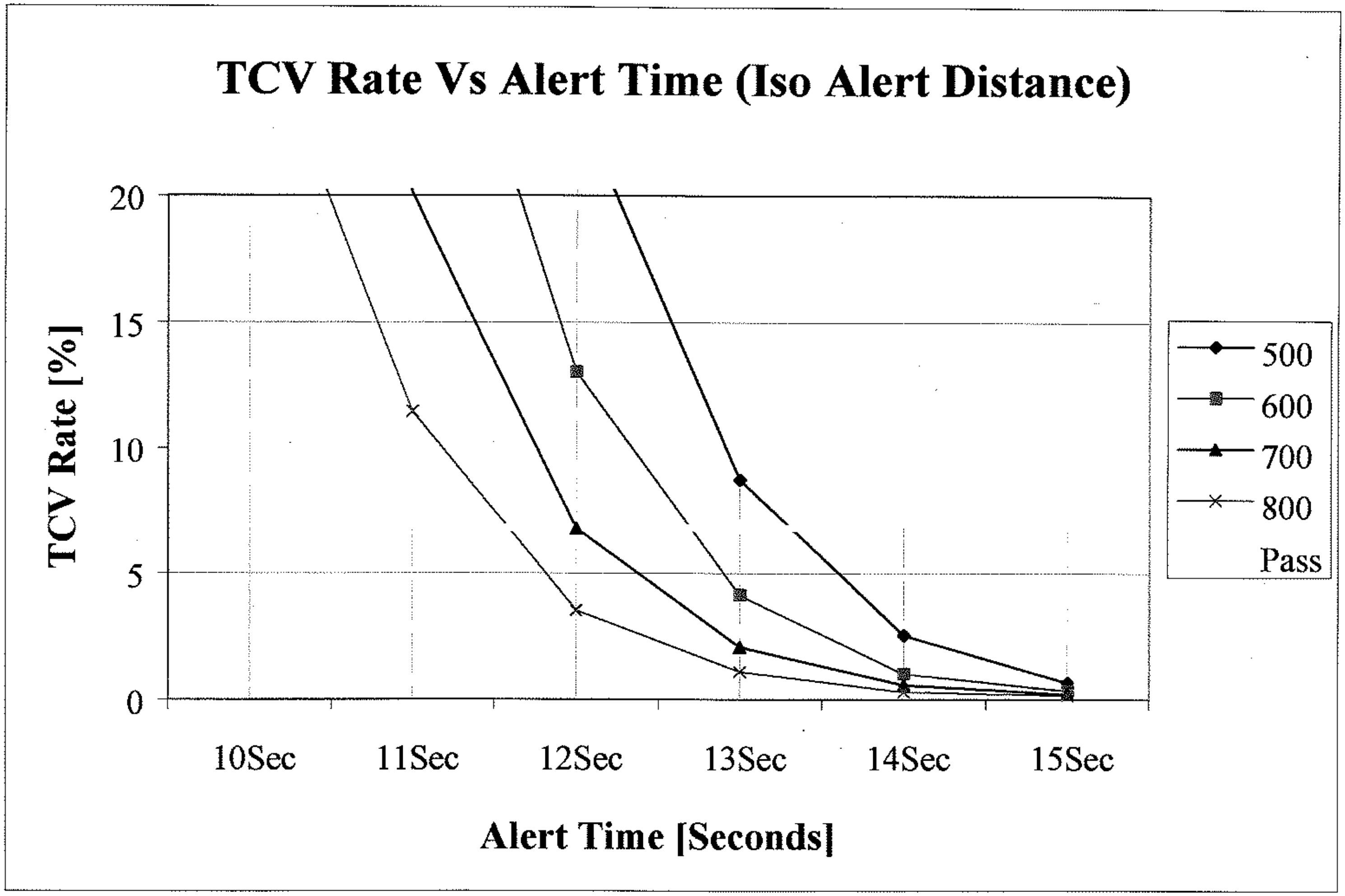


Chart B-2: CONSTANT PILOT RESPONSE TIME: 2.5 SECONDS (ZOOMED VIEW)

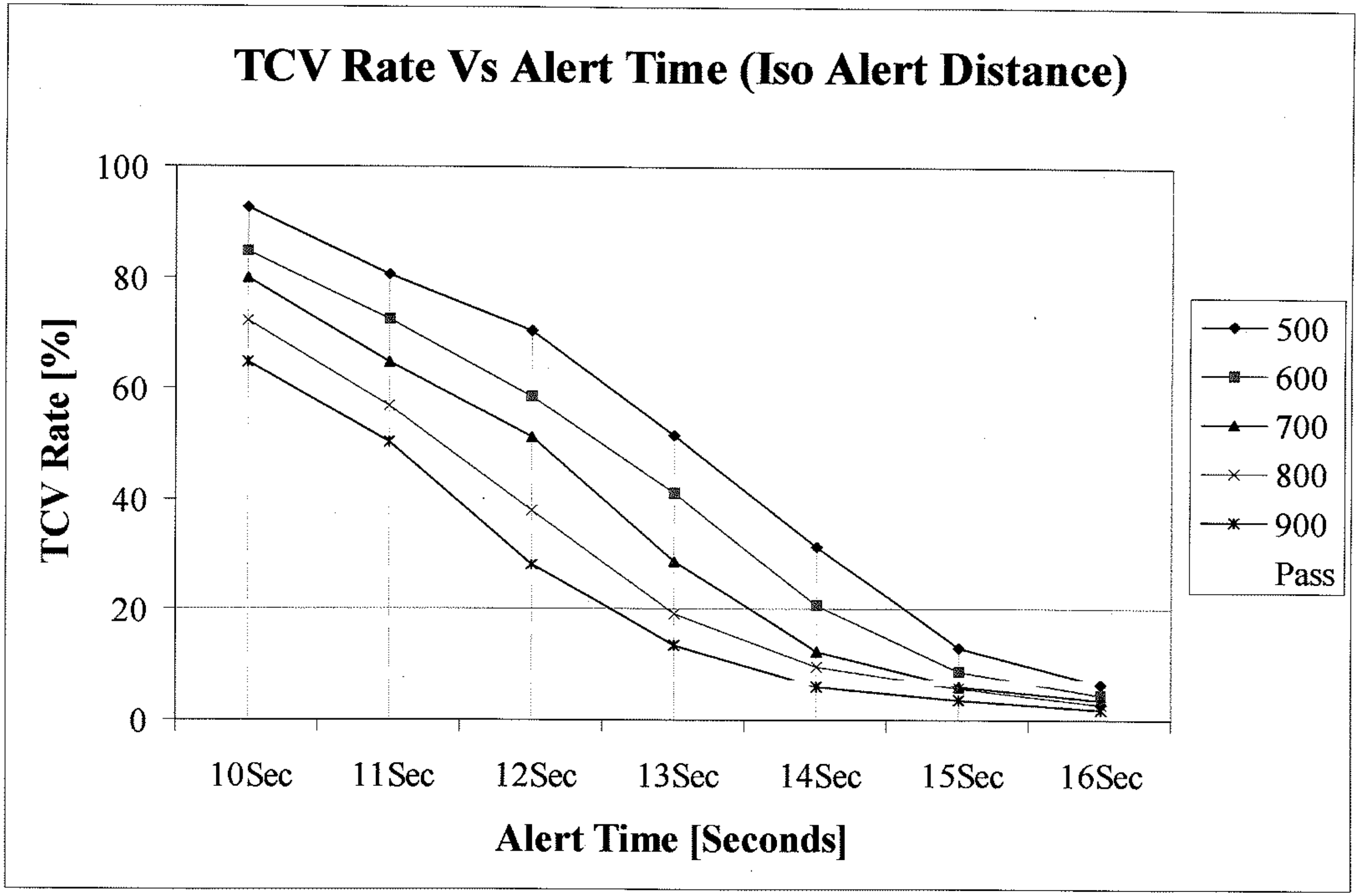


Chart B-3: TCAS PILOT RESPONSE TIME

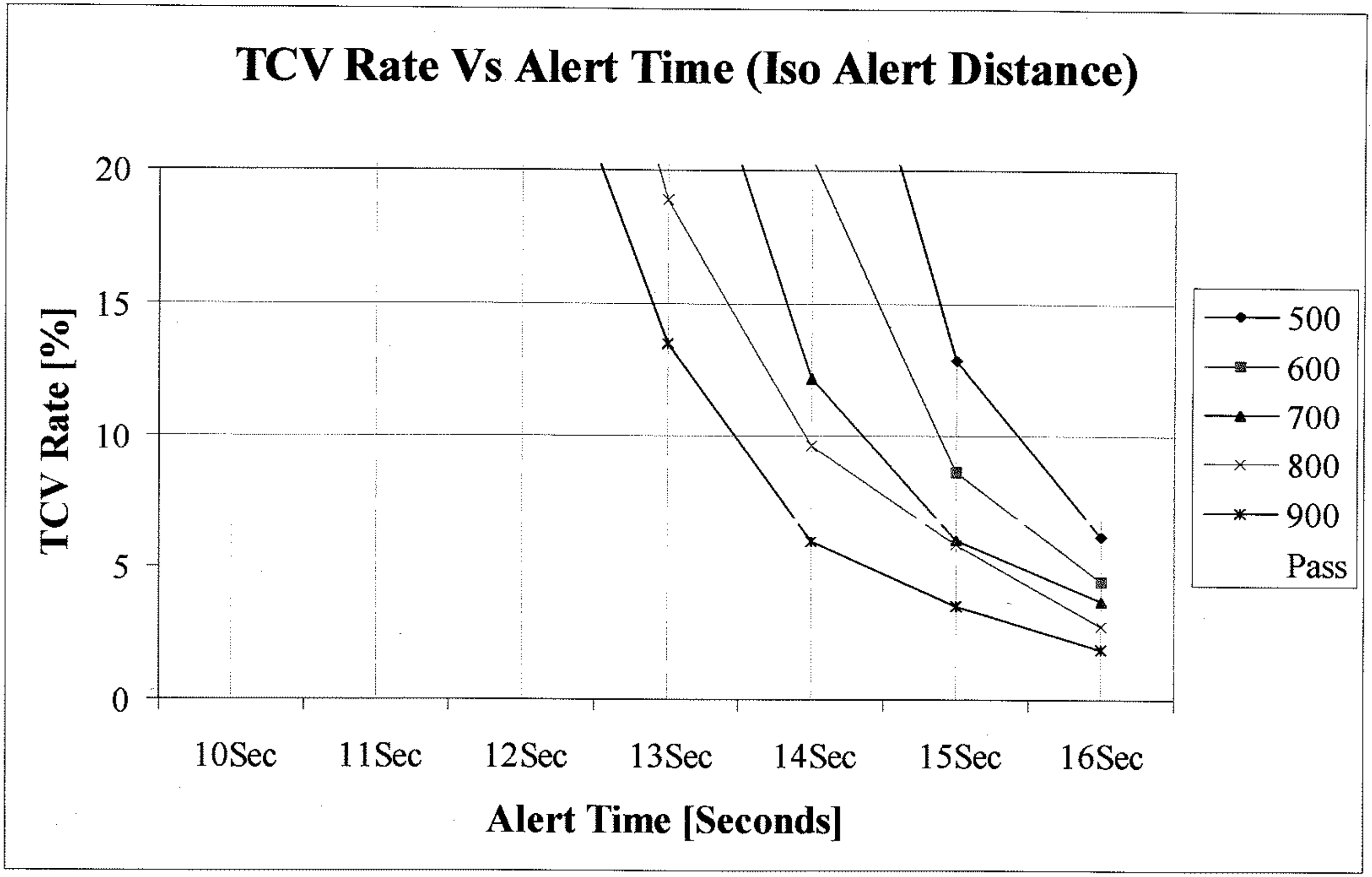


Chart B-4: TCAS PILOT RESPONSE TIME (ZOOMED VIEW)

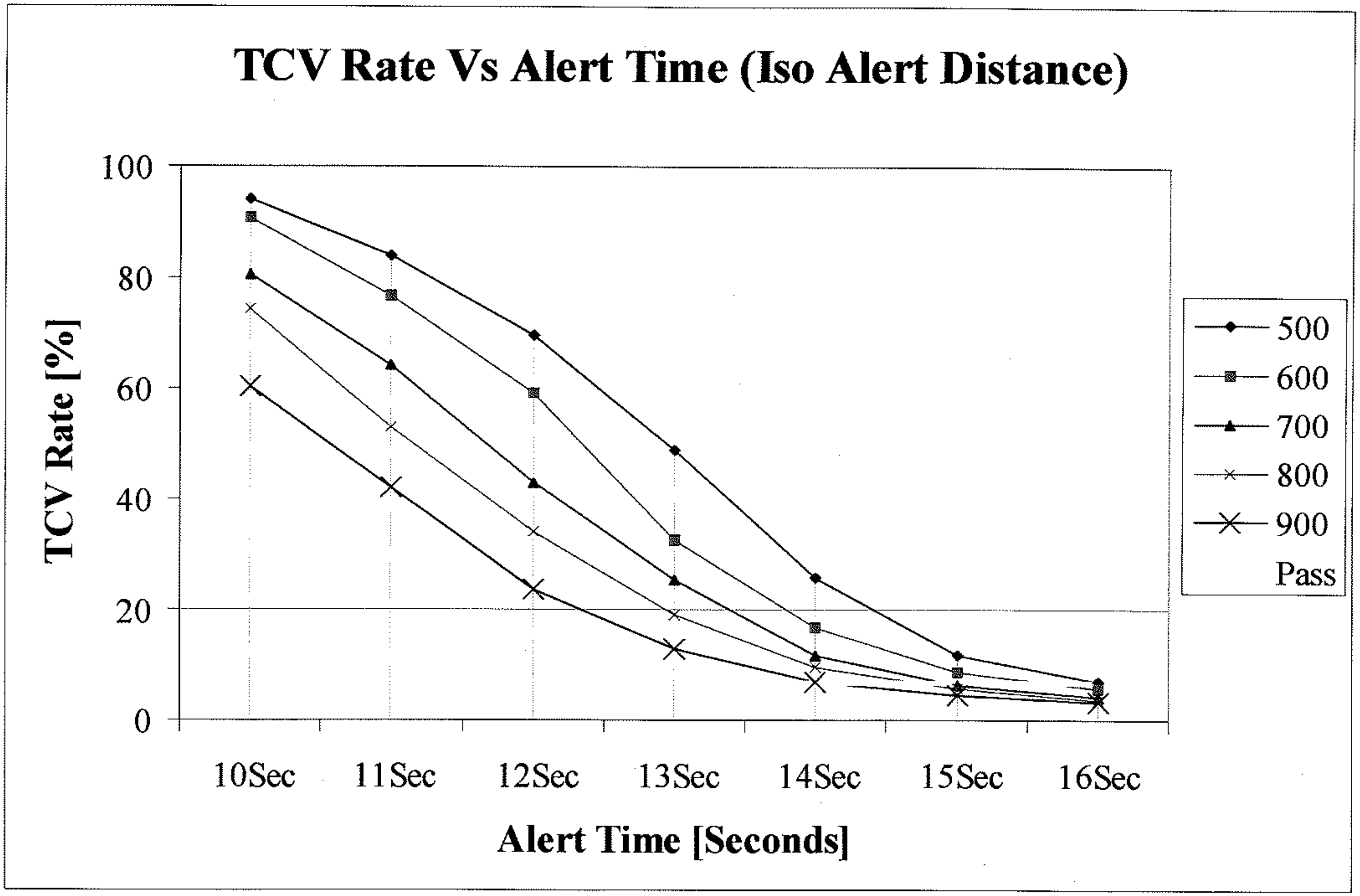


Chart B-5: PRM PILOT RESPONSE TIME

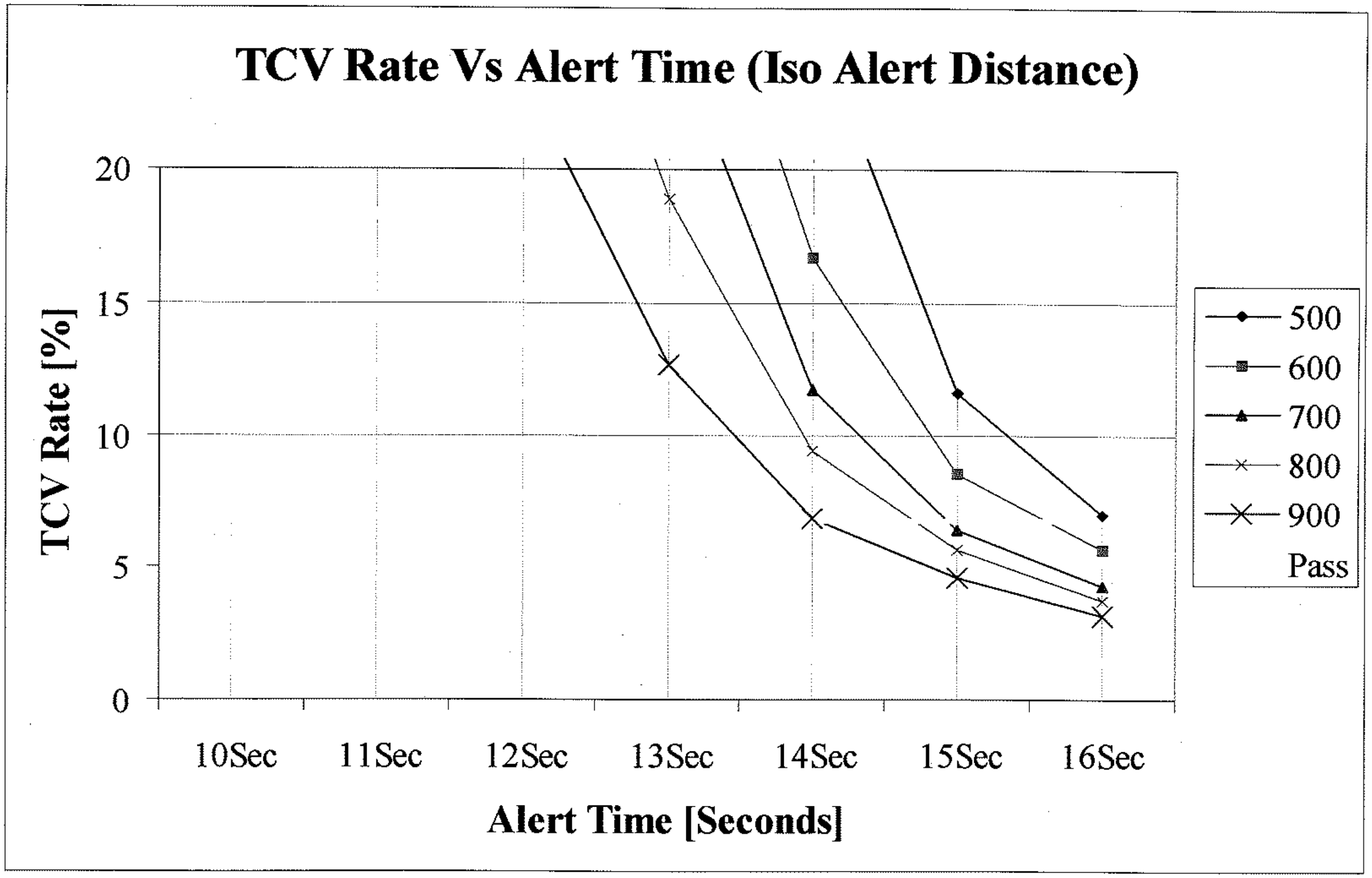


Chart B-6: PRM PILOT RESPONSE TIME (ZOOMED VIEW)