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A METHOD FOR THE STUDY OF CATEGORY III AIRBORNE PROCEDURE RELIABILITY

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16. Abstract

A method for the study of Category III airborne-procedure reliability is presented. The method, based on PERT concepts, is considered to have utility at the outset of a procedure-design cycle and during the early accumulation of actual performance data. For purposes of illustration, the method is exercised on a procedural set drawn from an earlier study of all-weather-system reliability.

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PREFACE

The technique described herein was developed in conjunction with a program at the U.S. Department of Transportation, Transportation Systems Center (TSC) to aid in the development of a Category III all-weather-landing capability in the United States. The program is sponsored by the Systems Research and Development Service of the Federal Aviation Administration.

Initial specifications for the conduct of Category IIIA operations and for the hardware and systems required for their support have been drafted. The primary objective of the work at TSC is to identify further requirements in the areas of automatic landing guidance, airport design, and ground/airborne procedures which must be met to achieve the desired level of safety.

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1. INTRODUCTION

Rather significant difficulties attend an effort to assess the overall reliability of a complex collection of hardware and procedure elements, such as that represented in the Category III all-weather-landing system. The reliability of each piece of hardware is generally known on the basis of bench or field test, or is estimable from known internal component reliabilities. The process of combining these variables to arrive at estimates of probability of failure (or success) is relatively straightforward. Such is not the case, however, for those aspects of system function which are implemented by the (human) administration of procedures since the inherent reliability of this administration is not similarly amenable to specification.

Efforts to render such specification have been in progress for many years. These efforts have resulted in long lists of what the human operator can be expected to do well, and what he can be expected to do poorly, as compared, for example, with a machine.[1] Some of these efforts have resulted in the assignment of probabilities of failure (or success) based on laboratory observations or simulations of human performance in selected portions of total tasks or on statistical estimates drawn from actual operations.[2] Quite clearly, these efforts have been helpful in providing design guidelines and screening out of aspects of procedure which place excessive demands on human performance. They have not, however, provided data specific enough for detailed design of the total complex of rules and procedures which must support new or more stringent system functions.

The planners and fabricators of the complex systems which will support all-weather-landing operations have been, and still are, faced with design considerations in which human reliability figures as an important decision parameter. On the basis of studies and reports of pilots' landing in low visibility, it is clear that the manual control task is difficult at best (with current instrumentation), and that the stress levels which can be reached under these conditions may affect performance adversely. Thus, the decision has been made to employ automatic landing systems in at least the first generation of Category III aircraft and to provide levels of redundancy, such that normal (automatic) system operation is maintained within specified limits in the presence of one or more failures.

Category III operations have not yet begun in the United States. As of this writing, only one airport (Dulles International in Washington, D.C.), and three aircraft types (the McDonnel Douglas DC-10, the Lockheed L1011 and a configuration of the Boeing 747), are equipped for landing under Category IIIA conditions (zero decision height, 700-foot RVR). In no instance to date, has the airport/aircraft complex been "exercised" under actual Category IIIA conditions. As a result, the data which are required for an orthodox statistical analysis of reliability and safety are lacking. The procedures which will be employed in support of these operations are, however, in the process of definition.

The purposes of this report are first, to suggest that, despite the lack of "hard" information relating to human reliability in general and the absence of Category III operational data specifically, a preliminary analysis of the temporal characteristics of airborne procedures can be conducted which can be of aid in pinpointing potential areas of concern, and second, to discuss and illustrate a technique with which to implement such an analysis.

With respect to the latter purpose, it should be noted that all data utilized in the illustration were collected in the course of an earlier study of all-weather landing systems and, as such, may not be representative of procedures currently intended for Category III operations. It is most important to recognize that our concern at the moment is more with the intention and form of the analyses to be made than with the timeliness of the data.

2. STRATEGIES FOR STUDY OF PROCEDURE RELIABILITY

At least two different strategies might be pursued in the study of procedure reliability. The most desirable of them would capitalize on experience already accrued with a given set of procedures and amount largely to an extrapolation from this "sample" experience to a total ("parent") population of experience. A major requirement in such an extrapolation would be for data which takes the form of errors committed per number of specific procedure executions. The prime emphasis would be on predicting the accuracy of performance over repeated administrations of the procedure.

A second strategy might concentrate on the temporal constraints under which a given set of procedures is executed. This approach could have utility when performance accuracy data have not yet accumulated in sufficient quantity so as to permit extrapolation to a "parent" distribution. The goal here would be to determine the relative distribution of slack times (that is, the times not explicitly allocated to a defined task) among individual tasks making up a procedure. A major assumption in this approach would be that in a temporal sequence of (reasonably) closely spaced procedures, the likelihood of an error is related inversely to the amount of slack available. As such, this assumption could be considered a variation of the argument that the greater the task loading per unit time, the higher the probability of an error in performance.

As noted in the above section, Category III airborne procedures are in the process of definition. Hence, the type of data that would be required to pursue the second of these strategies is becoming available. What is not available, at least within this context, is a method for treating the data in such a manner that quantitative assessments of safety and/or reliability can be made.

2.1 REQUIREMENTS FOR ANALYSIS BASED ON TEMPORAL CHARACTERISTICS

2.1.1 Note on Distinction between "Procedure" and "Task"

Throughout the remainder of this report, a distinction will be made between the terms, "procedure" and "task", which, although somewhat arbitrary, has value for interpretive purposes. We shall reserve the term "procedure(s)" for those activities which constitute major milestones in the approach and landing sequence. The term "task(s)" will be reserved for those discrete activities of which a procedure is composed. In the application to be illustrated, such activities as "performs AWLS enroute test," "prepares for LOC intercept," etc., will be considered to be "procedures;" while "disengages A/P by pressing A/P disconnect button," "depresses AWLS test switch," "depresses VOR/ILS button on NAV selector," etc., will be considered to be tasks.

2.1.2 Discussion

In simplest terms, the goal of an analysis based on temporal characteristics of a procedure is the generation of an estimate of the probability that the individual tasks making up a procedure (hence, the procedure itself), will be completed in the time allocated. If a given procedure has associated with it an intermediate to low probability of completion, the conclusion may be drawn that the occurrence of unexpected events during its execution will be such as to:

a. delay the start of the next procedure in the sequence, or

b. force the operator to increase the tempo of execution to complete the current procedure and to avoid the delay of the next procedure in the sequence; hence, possibly to increase the risk of an error.

Thus, the analysis, though not providing a direct estimate of the probability of (administrative) error, can aid in the identification of procedural areas, where the net effect of time stress may be to augment whatever unreliability is inherent to start with.

To perform such an analysis, it is necessary that certain temporal parameters of the subject procedures be known or estimable. They are as follows:

a. the minimum time required for completion of the task (or procedure),

b. the modal (most frequently observed) time for completion of the task (or procedure), and

c. the maximum time allowable for completion of the task (or procedure).

With these data and information concerning the way in which they are related (i.e., information about the distribution of times between the minimum and maximum allowable), an "expected" completion time can be calculated. The probability that this "expected" completion time falls within the maximum allowable time can then be determined.

Both the minimum and modal times are straightforward as regard definition. The minimum time is simply the time absolutely required to perform a given task. In those cases where the task is to set a switch, it may represent only the time involved in the movement of the hand and, as such, be very close to zero. In general, the minimum time is of relatively little interest. Its major importance is that its specification aids in establishing one end point of the distribution of performance times for a given task or procedure.

The modal time to complete a procedure is of considerably more interest since it reflects either the time actually taken by the greatest number of administrators, or the time estimated by those administrators to be representative of the greatest number.

A rationale for choosing maximum allowable times in the context of Category III procedures is more difficult to come by. What one seeks here is the analog of the "scheduled completion date," or "scheduled delivery date," familiar in the context of PERT analyses of production programs. In effect, it is necessary to find a set of "natural" events which "pace" the accomplishment of the procedures. The requirement is for a nominal sequence of ("milestone") events, before each one of which, a given set of tasks must be completed. Such events as "inbound procedure turn," "localizer intercept," "glide slope capture," "arrival at decision height (if defined)," "arrival at flare altitude," etc., conform to the requirements, and together they constitute the needed sequence.

Given the conceptual end points (as represented by the minimum and maximum times) of a frequency distribution of completion times and a measure of central tendency (the mode) it is next of concern to establish the shape of the distribution between points. Since the data which would be required to establish this distribution empirically are not yet available in the Category III program, it is necessary to choose from among the many possible distributions on more intuitive grounds. The Beta distribution has been chosen for the reasons discussed in the next section.

2.1.3 Comments on Use of Beta and Normal Distributions

As a representation of the probability of completing a task in a given amount of time, the Beta distribution[3] has considerable intuitive appeal. With highly trained and experienced personnel, it seems reasonable to expect that, other things being equal, familiar tasks will be performed in a period of time which more closely approximates the minimum time required for accomplishment than the maximum time available. Also, it seems reasonable to expect that estimates made by trained and experienced personnel of how long it takes to perform a familiar task are more likely to be optimistic than pessimistic; that is, to under estimate rather than to over estimate the time required. The distribution has the additional tangible advantage of having had fairly extensive empirical validation in PERT analysis of program management schedules.

It should be noted that, despite its "appeal" and "empirical validation," some controversy surrounds the basic assumption that the minimum required (t_o), modal (t_f), and maximum allowable (t_p) times are fitted into a Beta distribution, whose standard deviation is one-sixth of the range from t_o to t_p.[4] This appears, however, to be an issue that only actual completion time data on each and every task can help clarify. In the absence of such data and as a first approximation, the Beta distribution seems to be entirely adequate.

Of additional concern is the shape of the distribution describing the total set of procedures. Outside the immediate PERT context, efforts have been made to characterize the probability density function which best describes the composite of completion times for a set of independent and combined (sub-) tasks.[5] Results have indicated the possibility of representing such a composite with a Weibull or weighted-Weibull distribution. Computer simulations have, on the other hand, frequently treated task completion times as normally distributed.[6] At the risk of being somewhat arbitrary, it has been herein assumed that the composite of individual completion times is normally distributed, and that the mean and variance of this distribution are equal, respectively, to the sum of means and sum of variances of the individual procedure distributions. This choice is based primarily on the following two considerations:

a. The procedure sets of interest normally contain a fairly large number of tasks. Unless the individual distributions of these tasks are systematically skewed positively or negatively, the overall distribution is likely to be normal, and

b. The relative contribution of individual procedure variances to the total temporal variance in the set of procedures is being estimated. The temporal variances of these individual procedures are much more a function of the range between t_o and t_p than of the precise distributions of completion times.

3. DEVELOPMENT OF METHOD

The assumptions and definitions required in the proposed analysis are essentially those of PERT. It is well to review the more important of these before presenting an illustration of the method.

3.1 ASSUMPTIONS

a. It is possible to estimate the shortest time (t_o) necessary to complete a given element of procedure.

b. It is possible to estimate the longest time (t_p) allowable for the completion of a given element of procedure, when that element is located within a larger sequence which must be accomplished by the end of a specified period.

c. The frequency distribution of each procedure-element completion time has a single modal value (t_f).

d. From t_o, t_p, and t_f, it is possible to generate a valid estimate of the expected time for completion (t_e) for each procedure element using a Beta distribution.

e. The sum of the expected times (t_e) of all individual elements of a total procedure provides a valid estimate of the expected time required to complete the total procedure (T_e).

f. The difference (Δt) between T_e and the time allowed for completion (T_p) of the total procedure (by virtue of its design) provides an indication of the degree to which unscheduled events requiring attention may stress the accomplishment of the procedure.

g. The ratio between Δt and the standard deviation (σ) of the normal probability density function, into which T_e and T_p are fitted, provides an estimate of the probability that the procedure will be completed in the allowable time.

3.2 DEFINITIONS

The definition of expected time to completion of a task is

$$t_e = \frac{t_o + t_p + 4t_f}{6}, \tag{3-1}*$$

where t_o = the shortest time required (the "optimistic" time),

t_p = the maximum time allowed (the "pessimistic" time),

t_f = the time most frequently taken (i.e., the mode).

The variance (σ^2) of the probability density function is given as

$$\sigma^2 = \frac{(t_p - t_o)^2}{36} \tag{3-2}$$

The total expected time to completion of a set of <u>n</u> task elements, each member of which has an expected time (t_{e_n}) is

$$T_e = \sum_{i=1}^{n} t_{e_i}, \tag{3-3}$$

where t_{e_i} = the expected time to completion of the $i^{\underline{th}}$ task element.

And, the total variance is

$$\sigma^2 (T_e) = \sum_{i=1}^{n} \sigma^2 (t_{e_i}) \tag{3-4}$$

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*This equation is a commonly used linear approximation (in PERT applications) of the cubic equation, $\alpha^3 + (36r^3 - 36r^2 + 7r)\alpha^2 - 20r^2\alpha - 24r^3 = 0$. A simplified derivation is given in Appendix A to this report.

With the individual and total variances thus defined, it is possible to express the contribution of the variance of a given task element to the total variance as a percentage:

$$\sigma^2 (t_e) / \sigma^2 (T_e) , \tag{3-5}$$

and to rank the task elements in terms of decreasing contribution to the total procedure variance. In addition, it is possible to determine the probability (P_s) that the total procedure can be completed in the time allowed, by computing the ratio:

$$P_s = \frac{T_p - T_e}{\sigma} , \tag{3-6}$$

and entering the result in a normal probability distribution table.

The probability of failing to complete the procedure (P_f) is, of course,

$$P_f = 1 - P_s . \tag{3-7}$$

4. ILLUSTRATIVE APPLICATION

4.1 CONVENTIONS

For purposes of illustrating the application of this technique, a portion of the Lockheed-Georgia (1967)[7] data, developed in the course of an earlier study of all-weather landing system reliability, has been used (with modifications). It is important to note that these data were not collected with such an analysis in mind.* As a result, the following conventions were adopted to make the data suitable for analysis:

a. Except where indicated, the tasks listed are sequential in character. That is to say, the task currently being performed must be completed before the next required task can be started.

b. Except where indicated, a task performed by one member of the crew is not performed in parallel by another member of the crew.

c. The task durations listed by Lockheed-Georgia are assumed to be representative of modal times (t_f).

d. Minimum required times (t_o) for any of the tasks listed are arbitrarily defined to be 20 percent shorter than their corresponding t_f.

e. The maximum allowable time (t_p) for any given task is (arbitrarily) defined to be equal to the starting time for the next task in the sequence, as indicated in the earlier study.

f. All listed tasks must be performed.

g. The sets of tasks and procedures listed are formally exhaustive over the time period analyzed. That is to say, all activities which must be performed in the time interval are listed.

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*A suggested format for the collection of data required in future analyses is provided in Appendix B.

4.2 APPLICATION

Table 4-1 presents tasks and procedures as listed by Lockheed-Georgia,[7] and their associated durations. Column two (Task Time) of the table contains the individual task durations. Column four (Sum of Observed Task Times, t_f) totals those durations within procedure elements. The values in column three (Total Allowable Time, t_p) represent the maximum time which can elapse from the starting time of the $n^{\underline{th}}$ procedure to the starting time of the $n+1^{\underline{st}}$ procedure.* Values in column five (Minimum Required Time, t_o) are simply 80 percent of the associated t_f , or, 0.8 t_f.

Table 4-2 is a summary of expected time (t_e), standard deviation (σ), and variance (σ^2) for each procedure element contained in Table 4-1. Expected times are calculated from the formula:

$$t_e = \frac{t_o + t_p + 4t_f}{6} ,$$

and variances from the formula:

$$\sigma^2 = \frac{(t_p - t_o)^2}{36}$$

4.3 DISCUSSION

Since the data used in the illustrative application above were not collected with the present treatment in mind, little is to be gained from an attempt to interpret specific analytic outcomes. It is appropriate, however, to discuss the form such an interpretation might take.

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*Such times were determined from entries in column five (Time to Touch Down) of Lockheed-Georgia's table XXIII (see Reference No. 7) by subtracting each successive time value from the time value immediately before it.

TABLE 4-1

TOTAL ALLOWABLE, MODAL AND MINIMUM REQUIRED TIMES FOR SELECTED PROCEDURES[7]

Task/Procedure	Task Time (seconds)	Procedure Time (seconds)		
		Sum of Observed Task Times (t_f)	Total Allowable Time (t_p)	Minimum Required Time (t_o)=$0.8t_f$
1. Performs flight director tests		30.00	30.00	24.00
2. Performs AWLS enroute test			6.00	
2.1 Disengages A/P by pressing A/P disconnect button	0.2			
2.2 Depresses AWLS test Switch	1.4			
2.3 Positions AWLS control Switch to AWLS position	2.0	3.60		2.88
3. Monitors fault lights during test		174.00	180.00	139.00
4. Evaluates test information			324.00	6.72
4.1 (No faults indicated)	5.0			
4.2 Depresses AWLS switch to off	1.4			
4.3 Positions AWLS switch to off	2.0	8.40		
5. Prepares for LOC intercept			60.00	
5.1 Sets heading for base leg approach	6.0			

TABLE 4-1 (CONTINUED)

Task/Procedure	Task Time (seconds)	Procedure Time (Seconds)		
		Sum of Observed Task Times (t_f)	Total Allowable Time (t_p)	Minimum Required Time (t_o)=$0.8t_f$
5.2 Positions SEL/NORM switch to SEL	2.0			
5.3 Depresses VOR/ILS button on NAV selector	1.0			
5.4 Tunes Localizer	15.0			
5.5 Sets up AFCS control panel	4.0			
5.6 Sets course (Course Set) to runway heading	10.0			
5.7 Calls for before landing check	(in parallel)			
5.8 Sets power for approach speed	15.0			
5.9 Depresses auto-throttle button	0.2			
5.10 Turns radar altimeter on	1.2	54.40		43.52
6. Prepares for procedure Turn inbound			60.00	
6.1 Positions SEL/NORM switch to NORM	2.0			
6.2 Positions AWLS switch to AWLS	1.0			
6.3 Monitors ADI and flight instruments	Continuous			
6.4 Checks G/S ARMED light	1.0			
6.5 Sets airspeed	5.0			
6.6 Monitors aircraft heading change	6.0			
6.7 Sets airspeed	5.0	20.00		16.00

TABLE 4-1 (CONTINUED)

Task/Procedure	Task Time (seconds)	Procedure Time (seconds)		
		Sum of Observed Task Times (t_f)	Total Allowable Time (t_p)	Minimum Required Time (t_o)=$0.8t_f$
7. Performs tasks related to LOC intercept			90.00	
7.1 Monitors localizer Intercept	20.0			
7.2 Monitors ADI and other flight instruments	continuous			
7.3 Sets heading (Heading Set) to missed approach heading	6.0	26.00		20.80
8. Prepares for glide Slope Capture			90.00	
8.1 Calls for landing flaps	12.0			
8.2 Calls for lowering of landing gear	20.0			
8.3 Reduces airspeed to 1.3 Vs	5.0			
8.4 Monitors ADI and other flight instruments	continuous			
8.5 Observes onset of G/S progress display light	0.7	37.70		30.16
8.6 Monitors rate of descent and other flight instruments	continuous			

TABLE 4-1 (CONTINUED)

Task/Procedure	Task Time (seconds)	Procedure Time (seconds)		
		Sum of Observed Task Times (t_f)	Total Allowable Time (t_p)	Minimum Required Time (t_o)=$0.8t_f$
9. Monitors final stages of landing			30.00	5.36
9.1 Observes onset of land arm progress display	0.7			
9.2 Monitors flight Instruments and External environment	Continuous			
9.3 Notes altitude at 300 ft.	2.0			
9.4 Notes altitude at 200 ft.	2.0			
9.5 Notes altitude at 100 ft.	2.0	6.70		5.36
9.6 Makes (go-no-go) decision				

TABLE 4-2 SUMMARY OF EXPECTED TIME, STANDARD DEVIATION, AND VARIANCE FOR EACH MAJOR PROCEDURE

Procedure Element	Expected Time (seconds)	Standard Deviation (σ)	Variance (σ^2)
1. Performs F/D tests	29.0	1.00	1.00
2. Performs AWLS enroute test	3.88	0.52	0.27
3. Monitors fault lights during rest	169.20	6.80	46.24
4. Evaluates test information	60.72	52.88	2796.29
5. Prepares for localizer intercept	53.52	2.74	7.51
6. Prepares for procedure turn inbound	26.00	7.33	53.73
7. Performs tasks related to localizer intercept	35.80	11.53	132.94
8. Prepares for glide slope capture	45.16	9.97	99.40
9. Monitors final stages of landing	10.36	4.11	16.89
			3178.06

Earlier it was noted that the prime goal of an analysis of the sort proposed here is the identification of what might be called "soft spots" in procedure sequence; i.e., areas where changes in cockpit tempo caused by fatigue, diversions of attention, or other stressful factors might reduce the probability of accomplishment of formally prescribed tasks. Such "soft spots" could be indicated in the analysis by the existence of a very small difference between expected completion time and total allowable time. For the procedures presented here, differences between these times and the ranks of these differences are shown in columns four and five of Table 4-3.

TABLE 4-3 SUMMARY OF DIFFERENCES BETWEEN MAXIMUM ALLOWABLE AND EXPECTED TIMES FOR MAJOR PROCEDURE

Procedure	Maximum Allowable Time (t_p) (seconds)	Expected Time (t_s) (seconds)	Difference seconds	Rank
1.	30.00	29.00	1.0	1
2.	6.00	3.88	2.12	2
3.	180.00	169.20	10.80	4
4.	324.00	60.72	263.28	9
5.	60.00	53.52	6.48	3
6.	90.00	26.00	34.00	6
7.	90.00	35.80	54.20	8
8.	90.00	45.16	44.84	7
9.	30.00	10.36	19.64	5

On the basis of this information, one might anticipate that the nominal reliability of procedures one, two, and five could be compromised by the occurrence of an event which in any way reduced the tempo with which they were performed. With such "anticipations," it would be appropriate to study the task structure within those procedures to determine (a) if the equipment, task or task structure could be modified so as to leave more slack time; (b) if the procedure(s) could be relocated in time, that is, scheduled in connection with a procedure which has a significantly greater degree of slack;* and (c) what the actual variances of completion times are. Of these, the last is perhaps the most critical. If

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*For purposes of illustration, all procedures represented here require attention at the times indicated. It is important to note, however, that under real operating conditions, procedures 1 and 2 can be performed before takeoff. Hence, they would normally be of less concern than indicated in this discussion.

it can be found through (limited) observation of procedure administration under either actual operating conditions or through carefully designed simulations that the average times to completion are very stable; and further, that failure to complete the procedure does not place the system in jeopardy, one may be justified in allowing it to exist without modification.

Clearly, the heuristic value of this method in a given application is a function of the precision of the estimate of t_e. Although there is no technique for assuring the precision of this estimate before the fact, it does seem reasonable to assume that the smaller the variance of a given procedure (as defined here), the greater the confidence one can place in an observed difference between t_e and t_p. On these grounds from Table 4-3, the observed differences in procedures 4, 7, and 8 may be suspect, while those observed in procedures 1, 2, 5, and 9 may be considered to be highly valid. Differences observed in procedures 3 and 6 have an intermediate degree of validity. This grouping is more obvious from an inspection of Table 4-4, where the contribution of each procedure to the total variance over all procedures is shown as a percentage. Here, it can be seen that procedures 4, 7, and 8 collectively account for in excess of 95 percent of the total variance; procedures 1, 2, 5, and 9, for less than 1 percent; and procedures 3 and 6 for slightly in excess of 3 percent.

The matter is important for at least two reasons: (a) procedures will be found which exhibit a very small difference between t_e and t_p <u>and</u> a low variance (e.g., procedure 2: $\Delta = 2.12$, $\sigma^2 = 0.27$). (If the low variance of such a procedure can be substantiated, modification of the procedure so as to create further slack time may have considerable merit.) (b) If the variances of each procedure in the total set have a high degree of validity, they can be ordered in terms of decreasing magnitude, and thus, serve as a guide for the most appropriate accommodation of additional tasks which are not constrained to fit into particular sequences.

TABLE 4-4 RATIO OF INDIVIDUAL TASK VARIANCES TO TOTAL VARIANCE

Task Element	n^2/T^2 %	Rank
1. Performs F/D tests	0.03	8
2. Performs AWLS test	0.01	9
3. Monitors fault lights	1.45	5
4. Evaluates test information	87.99	1
5. Prepares for localizer intercept	0.24	7
6. Prepares for procedure turn inbound	1.69	4
7. Performs task related to localizer intercept	4.18	2
8. Prepares for glide slope capture	3.13	3
9. Monitors final stages of landing	0.53	6
	99.25	

4.4 DETERMINATION OF OVERALL RELIABILITY

The preceding discussion has been concerned with the characteristics of individual procedures. As indicated in section 3, the reliability of the whole set of procedures can be determined by considering that the probability of completing the total set by a given time is distributed normally about a mean equal to the sum of the individual t_e. The ratio between the area under the curve to the left hand of the maximum allowable time and the total area under the curve then represents the probability that the procedures set can be completed in the allowable time.

Using Equation 3-6 (Section 3), the probability of accomplishing the set of procedures listed here is equal to 7.741 units of standard deviation (σ) under the normal curve. Converting this value to P_s and employing the latter in Equation 3-7 (Section 3),

P_f is found to be less than 1 x 10^{-10}. It will be recognized that this value is far in excess of that required to meet the Category III safety goal (1 x 10^{-7}). With an exhaustive specification of tasks, it is unlikely such a low value would be generated in an analysis of this type.

5. BEYOND PRELIMINARIES

The method outlined herein represents a useful adjunct to a program concerned with establishing the reliability of man and machine elements in a Category III airborne system. It provides a way of identifying those procedures within a long and complex set which are particularly vulnerable to changes in tempo of administration. Since the analysis deals only with temporal parameters of the procedure set and not at all with accuracy of administration, it represents, in some sense, a best-case approach which can be implemented before and during the accumulation of actual operating experience. It is appropriate to consider now what might follow such a preliminary analysis.

On the assumption that the analysis has uncovered an area of possible concern, a number of questions should be asked:

a. What are the consequences of failing to administer the procedure?

b. What are the consequences of failing to administer the procedure within the scheduled time?

c. What types of errors in procedure administration could occur as a result of time stress?

d. What are the consequences of each of these types of error?

In some cases, answers to these questions will be very straightforward. In others, they may be less than apparent and require further analytic effort.

A technique which has considerable merit in such an effort is the fault-tree analysis, in which the possible causal sequences and hazardous conditions resulting therefrom are exhaustively described. Although the majority of earlier applications of this technique has been made with respect to failure of hardware subsystems,[8] there is no reason in principle why the basic rationale cannot be applied in the area of procedural systems. The major requirement here, as for the preliminary analysis discussed above, is for an exhaustive catalog of the individual tasks which must be performed within each time segment. And, in addition, there is a requirement for detailed knowledge of at least the immediate consequences to the integrity of the total system mission of unsuccessful administrations of procedure.

With the aid of the fault-tree technique, it should be possible to identify areas of procedure in need of the careful scrutiny which can be brought to bear during simulation or flight test. Procedures thus identified will have at least two undesirable characteristics: (1) a low tolerance for variation in tempo, and (2) a significant impact on system integrity in the event of unsuccessful accomplishment. The essential questions for further study will then concern the nature and likelihood of events which could produce the required variation.

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7.1 APPENDIX A

DERIVATION OF EQUATIONS FOR PROCEDURE-TIME ASSESSMENT[9]

The probability density function of the Beta distribution is given as

$$f(t) = K\ (t - o)^{\alpha}\ (p - t)^{\gamma}\ , \qquad \text{(A-1)}$$

where K, α, and γ are functions of o, f, and p, respectively, and o, f, and p are earliest, most likely, and latest times, respectively.

The probability density function is set equal to 1, by setting the range between o and p equal to 1.

$$p - o = 1, \qquad \text{(A-2)}$$

and rescaling the time scale (t) to a new scale (x),

$$x = \frac{t - o}{p - o} . \qquad \text{(A-3)}$$

The modal time is

$$r = \frac{f - o}{p - o} , \qquad \text{(A-4)}$$

and

$$\alpha = f - o, \qquad \text{(A-5)}$$

$$\gamma = p - f. \qquad \text{(A-6)}$$

The expression for the modal time is, then

$$r = \frac{\alpha}{\alpha + \gamma} \quad , \qquad \text{(A-7)}$$

Variance of (X) is given as

$$\sigma_x^2 = \frac{(\alpha + 1) \ (\gamma + 1)}{(\alpha + \gamma + 2)^2 \ (\alpha + \gamma + 3)} \quad . \qquad \text{(A-8)}$$

Assume that the standard deviation, σ, is equal to one-sixth of the range,

$$\sigma = \frac{p - o}{6} = \frac{1}{6} \ . \qquad \text{(A-9)}$$

Then,

$$\sigma^2 = \frac{(\alpha + 1) \ (\gamma + 1)}{(\alpha + \gamma + 2)^2 \ (\alpha + \gamma + 3)} = \frac{1}{36} \qquad \text{(A-10)}$$

Substituting (A-7),

$$\alpha^3 + (36r^3 - 36r^2 + 7r)^2 - 20r^2 \alpha - 24r^3 = 0. \qquad \text{(A-11)}$$

The expected value of x is given as

$$\varepsilon(x) = \frac{\alpha + 1}{\alpha + \gamma + 2} \ . \qquad \text{(A-12)}$$

A straight-line approximation is given as

$$\varepsilon(x) = \frac{4r + 1}{6} \ . \qquad \text{(A-13)}$$

Substituting from (A-4) and using the expression for $\varepsilon(x)$,

$$\varepsilon(x) = \frac{f - o}{p - o} , \tag{A-14}$$

$$t_e = \frac{o + 4f + p}{6} . \tag{A-15}$$

7.2 APPENDIX B

SUGGESTED FORMAT FOR COLLECTION OF PROCEDURE-TIME DATA

PROCEDURE		TASK		Minimum Time to Complete (t_o)	Most Frequent Time (t_f)	Latest Allowable Time (t_p)	Expected Time (t_e)
Description	Duration	Description	Duration				
							(calculated values)
Sum of Recorded Times							

7.3 APPENDIX C

LIST OF TERMS

RVR	-	Runway Visual Range
PERT	-	Program Evaluation and Review Technique
AWLS	-	All Weather Landing System
LOC	-	Localizer
A/P	-	Auto Pilot
VOR/ILS	-	Very High Frequency Omni Range Radio/ Instrument Landing System
NAV	-	Navigation (Selector)
SEL/NORM	-	(Navigation) Selector/Normal
AFCS	-	Automatic Flight Control System
G/S ARMED	-	Glide/Slope (Capture Mode) Engaged
ADI	-	Attitude Direction Indicator
V_s	-	Vertical Speed