JOURNAL OF AIRCRAFT
Vol. 48, No. 4, July–August 2011

Two Men in a Cockpit: Casualty Likelihood if One Pilot Becomes Incapacitated

Ephraim Suhir*
University of California, Santa Cruz, Santa Cruz, California 95064-1077
and
Richard H. Mogford†
NASA Ames Research Center, Moffett Field, California 94035-1000

DOI: 10.2514/1.C031263

A double-exponential probability distribution function of the extreme-value-distribution type is introduced to quantify the likelihood of a human's failure to perform his/her duties when operating a vehicle: an aircraft, a spacecraft, a boat, a helicopter, a car, etc. As a possible illustration of the general concept, a situation is considered when two pilots operate an aircraft in an ordinary (normal, routine) fashion that abruptly changes to an extraordinary (offnormal, hazardous) one if one of the pilots becomes incapacitated for one reason or another. Such a mishap is referred to as an *accident*. Because of the accident, the other pilot, the pilot in charge, might have to cope with a higher mental workload. A fatal casualty will occur if both pilots become unable to perform their duties. Although this circumstance will eventually manifest itself only during landing, in order to assess the probability of the potential casualty, an en route situation (i.e., a situation that precedes descending and landing) is nonetheless considered. This probability depends on the capability of the pilot in charge to successfully cope with the increased mental workload. We determine the probability of a casualty as a function of the actual mental-workload level and the level of the human-capacity factor. The total flight time and the time after the accident are treated in the analysis as nonrandom parameters. The suggested mental-workload/human-capacity-factor model and its generalizations, after appropriate sensitivity analyses are carried out, can be helpful when developing guidelines for personnel training, when choosing the appropriate flight simulation conditions, and/or when there is a need to decide if the existing level of automation and the navigation instrumentation and equipment are adequate to cope with extraordinary (offnormal) situations. If not, additional and/or more advanced instrumentation and equipment should be considered, developed, and installed. Plenty of additional risk analyses and human-psychology-related effort will be needed, of course, to make the guidelines based on the suggested probabilistic risk-management extreme-value-distribution model practical.

Nomenclature

F	=	human-capacity-factor level
F_0	=	most likely (specified) human-capacity factor
G	=	mental-workload level
G_0	=	most likely (specified) mental workload
H	=	entropy (uncertainty) of the probability density function of the human failure
$P(F)$	=	probability of human failure
R	=	probability of human nonfailure, $1 - P$
T	=	total time of operation (mission)
t	=	elapsed time of operation (mission)

I. Introduction

CONSIDERABLE improvement in various vehicular (aerospace, maritime, automotive, railroad, etc.) technology situations can be expected through better ergonomics, better work environment, and other means that directly affect human behavior and performance. There is also an opportunity (potential) for a further reduction in vehicular casualties through better understanding the role that various uncertainties play in the operator's world of work. By employing quantifiable and measurable ways to assess the role of these uncertainties and by treating a human in the loop as a part (often, the most crucial part) of a complex man–instrumentation–equipment–vehicle–environment system, one could dramatically improve the human performance and could predict and, if needed, even specify and control a sufficiently low probability of the occurrence of a mishap. In this analysis we introduce a double-exponential probability distribution function (PDF) of the extreme-value-distribution (EVD) type to quantify the likelihood of a human failure to perform his/her duties when operating a vehicle. We consider, merely as an illustration, a situation when two pilots operate an aircraft in an ordinary (normal, routine) fashion that abruptly changes, because one of the pilots becomes incapacitated, to an extraordinary (offnormal, hazardous) situation. A fatal casualty will occur if both pilots become unable to perform their duties. Although this circumstance will most likely manifest itself only during landing, which is the phase of flight with the highest mental workload (MWL), we nonetheless address the en route condition (that precedes descending and landing) to determine how the likelihood of the pilot in charge (PIC) failure to perform his/her normal and offnormal duties might affect the probability of the potential casualty. We assess such a likelihood as a function of the operator's MWL and human-capacity factor (HCF). Our analysis is, in effect, an attempt to quantify, on the probabilistic basis, using a suitable analytical (mathematical) probabilistic risk-management (PRM) technique, the role that the human factor plays, in terms of the human's ability (capacity) to cope with an elevated MWL. The suggested EVD PDF considers the duration of the mission (flight, journey, task, and operation), the time in operation before and after the accident (when the MWL suddenly increases), and the relative levels of the MWL and the HCF: i.e., the human's ability to cope with the offnormal

Presented at the AIAA 2010 ATIO Conference , Fort Worth, TX , 13–15 September 2010; received 12 October 2010; revision received 2 December 2010; accepted for publication 2 December 2010.

*University of Maryland, College Park, MD; Chief Executive Officer, ERS Company, 727 Alvina Court, Los Altos, CA. Member AIAA.

†Research Psychologist, Human Systems Integration Division, Mail Stop 262-4. Member AIAA.

MWL. It is the relative levels of the MWL and HCF (these could be steady-state or time-dependent) that determine the likelihood of the mission success (safety).

Cognitive overload has been recognized as a significant cause of error in aviation, and therefore measuring the MWL has become a key method of improving safety. There is an extensive published work in the psychological literature devoted to the measurement of MWL, both in military and in civil aviation (see, e.g., [1–18]). A pilot's MWL can be measured using subjective ratings or objective measures [1,4]. The subjective ratings during simulation tests can be in the form of periodic inputs to some kind of data collection device that, e.g., prompts the pilot to enter a number between 1 and 7 to estimate the MWL every few minutes. Another possible approach is postflight paper questionnaires. There are some objective measures of MWL, such as, e.g., heart-rate variability. It is easier to measure the MWL on a flight simulator than in actual flight conditions. In a real aircraft, one would probably be restricted to using postflight subjective (questionnaire) measures, since one would not want to interfere with the pilot's work.

An aircraft pilot faces numerous challenges imposed by the need to control a multivariate lagged system in a heterogeneous multitask environment. The time lags between critical variables require predictions and actions in an uncertain world. The interrelated concepts of situation awareness and MWL are central to aviation psychology. The major components of situation awareness are spatial awareness, system awareness, and task awareness. Each of these components has real-world implications: spatial awareness for instrument displays, system awareness for keeping the operator informed about actions that have been taken by automated systems, and task awareness for attention and task management. Task management is directly related to the level of the MWL, as the competing demands of the tasks for attention might exceed the operator's resources: his/her capacity to adequately cope with the demands imposed by the MWL.

In modern military aircraft, complexity of information, combined with time stress, creates difficulties for the pilot under combat conditions, and the first step to mitigate this problem is to measure and manage the MWL. Although there is no universally accepted definition of the MWL and how it should/could be evaluated, there is a consensus that suggests that MWL can be conceptualized as the interaction between the structure of systems and tasks and between the capabilities, motivation, and state of the human operator. More specifically, MWL could be defined as the cost that an operator incurs as tasks are performed. Given the multidimensional nature of MWL, no single measurement technique can be expected to account for all the important aspects of it. Current research efforts in measuring MWL use psychophysiological techniques such as electroencephalographic, cardiac, ocular, and respiration measures in an attempt to identify and predict MWL levels. Measurement of cardiac activity has been a useful physiological technique employed in the assessment of MWL, both from tonic variations in heart rate and after treatment of the cardiac signal. The MWL depends on the operational conditions and the complexity of the mission; i.e., it has to do with the significance of the general task. The MWL is directly affected by the challenges that a pilot faces when he/she has to control the vehicle in a complex, heterogeneous, multitask, and often uncertain environment. Such an environment includes numerous different and interrelated concepts of situation awareness: spatial awareness for instrument displays, system awareness (e.g., for keeping the pilot informed about actions that have been taken by automated systems), and task awareness (which has to do with the attention and task management). Particularly, the offnormal MWL for a single pilot might be (but does not necessarily have to be) twice as high as the ordinary MWL.

As to the HCF, it considers, but might not be limited to, professional experience and qualifications; capabilities and skills; level of training; performance sustainability; ability to concentrate; mature thinking; ability to operate effectively in a tireless fashion under pressure and, if needed, for a long period of time (tolerance to stress); team-player attitude; swiftness in reaction, if necessary, etc.

The above factors affecting the MWL and HCF values are being studied extensively in the today's aviation psychology practice, and the available information can be effectively used to evaluate the most likely (ordinary, specified) values of the MWL and HCF. Such an evaluation is beyond the scope of our analysis, however. We simply assume that these values are deterministic parameters that are known (predetermined) in advance for a particular mission and for a particular individual. It is noteworthy that the ability to evaluate the absolute level of the MWL, important as it might be for noncomparative evaluations, is less critical in this study, which is aimed at the comparative assessments of the likelihood of a casualty when the MWL suddenly and significantly changes because of an unforeseeable accident.

The authors would like to point out also that we do not intend in this paper to come up with any accurate, completed, ready-to-go, off-the-shelf type of methodology. We realize that some readers might feel that our modeling is a bit simplistic from the avionic psychiatrist point of view, but we did not try to create a comprehensive model. Our intent is rather to illustrate how some PRM methods and approaches could be effectively employed to quantify the role of the human factor in situations of the type in question. We believe that the suggested model and its generalizations, after appropriate sensitivity analyses are carried out, can be helpful when developing guidelines for personnel training, when choosing the appropriate flight simulation conditions, and/or when there is a need to decide if the existing level of automation and/or the existing navigation instrumentation and equipment are adequate. If not, additional and/or more advanced instrumentation and equipment should be developed and installed. We also believe that the taken approach, with the appropriate modifications and generalizations, is applicable to many other situations (not necessarily in the avionic, or even vehicular, domain) when a human encounters an uncertain environment and/or a hazardous situation and/or interacts with never-perfect hardware and software. Plenty of additional engineering analyses and human-psychology-related efforts will be needed, of course, to make the guidelines (based on the suggested concept) practical and effective.

II. Analysis

A. Double-Exponential EVD-Type Probability Distribution Function

The following double-exponential PDF,

$$P(F) = 1 - \exp\left[-\frac{t}{T}\frac{G^2}{G_0^2}\exp\left(-\frac{F^2}{F_0^2}\right)\right] \tag{1}$$

of the EVD type (see, for instance, [19–22]) can be used to characterize and to quantify, on the comparative basis, the probability $P(F)$ of a vehicle operator's failure to perform his/her duties because of the mental overload and/or because of insufficient human capacity. In formula (1), t/T is the (nonrandom) ratio of the elapsed operation time, t, to the total duration, T, of the mission (flight) $(0 \leq t \leq T)$, G is the MWL level, G_0 is the most likely (specified, anticipated) value of the MWL for a pilot in ordinary flight conditions, F is the HCF level, and F_0 is its most likely (specified) value. The probability density function can be obtained, if necessary, from Eq. (1) by differentiation.

Formula (1) makes physical sense. Indeed, at the beginning of the flight $(t = 0)$ and/or when the MWL is very low $(G \to 0)$ and/or when the pilot is highly experienced, highly skilled, highly trained, and highly effective $(F \to \infty)$, the probability $P(F)$ that the pilot fails to carry out his/her duties is zero. When the pilot has to operate for an infinitely long time $(t \to \infty)$ and/or when the MWL is very high $(G \to \infty)$ while the HCF F is finite, then the human failure is inevitable: the probability $P(F)$ is equal to one.

B. Physical Meaning of the Double-Exponential Probability Distribution Function

From Eq. (1) we obtain, by differentiation,

$$\frac{\mathrm{d}P}{\mathrm{d}G} = 2\frac{H}{G} \tag{2}$$

where

$$H = -R \ln R \tag{3}$$

is the entropy of the probability $R = 1 - P$ of nonfailure (reliability) of the human to perform his/her duties. As follows from Eq. (2), the distribution (1) reflects a hypothesis that the change in the probability of failure (or nonfailure) with the change in the MWL level G is proportional to the entropy (uncertainty) H of the distribution of this probability and is inversely proportional to the workload level G. When the workload is certain ($H = 0$) and/or is very high ($G \to \infty$), the derivative dP/dG is zero: the probabilities P and R do not change with the change in the MWL level. When the load G is highly uncertain (large H value) and/or is very low ($G \to 0$), the derivative dP/dG is large: the probability of failure is highly dependent on the level of the workload.

The rationale behind the hypothesis (2) is that the change in the probability of failure with the change in the level of loading, such as MWL, is proportional to the degree of uncertainty. The latter is assessed as the ratio of the entropy of the distribution of the probability of failure to the level of loading. This ratio could be viewed as a sort of a random coefficient of variation (COV). Unlike the conventional COV, which is a nonrandom characteristic defined as the ratio of the standard deviation to the mean value of the random variable of interest, the COV in the right part of formula (2) is a random variable and is defined as the ratio of the (nonrandom) entropy to the (random) level of loading. Both the entropy and the loading level could be time-dependent: the demand (MWL) and the capacity (HCF) distributions might broaden (get spread out) in time and/or the gap between their most likely values might get narrower when time progresses.

C. Two Men in a Cockpit: Accidents and Casualties

The two pilots in a cockpit have overlapping duties. There would be more work for the PIC if his/her mate becomes incapacitated, but it is unclear, of course, to what extent the workload would actually increase. As is known, one of the main reasons for the today's two pilot operation practice is that one pilot can fly the aircraft alone, if needed. The aircraft and operation procedures are designed in such a way that this is indeed possible. In this analysis we assume, just to be specific, that the workload doubles as a result of the accident. The general PRM formalism will remain the same if the increase in the workload is much lower (perhaps more likely) or somewhat higher (less likely) than two.

Examine a situation that takes place at an arbitrary moment of time t after an aircraft takes off for a flight of the anticipated duration T and assume, for the sake of simplicity, that both pilots are identical (i.e., equally qualified, equally well trained, have equal HCFs, etc.) and that the MWL G is evenly distributed between them. Using formula (1), one can write the probability of failure for each of the pilots to perform his/her duties in the normal flight conditions as follows:

$$P_{0.5}(F) = 1 - \exp\left[-\frac{T-t}{T}\frac{G^2}{4G_0^2}\exp\left(-\frac{F^2}{F_0^2}\right)\right] \tag{4}$$

Note that if it were determined that, because of the accident, the increase in the MWL for the PIC is different from two, the factor 4 in the denominator in Eq. (4) could be changed so that the uneven distribution of the ordinary MWL is accounted for. If at the moment of time t that an *accident* takes place (one of the pilots becomes incapacitated), then his/her mate (PIC) will have to cope with the entire MWL G. The probability that the PIC fails during the remaining time $T - t$ to cope with the increased MWL can be expressed, assuming that the MWL doubles because of the accident, is

$$P_{1.0}(F) = 1 - \exp\left[-\frac{T-t}{T}\frac{G^2}{G_0^2}\exp\left(-\frac{F^2}{F_0^2}\right)\right] \tag{5}$$

Formulas (4) and (5) indicate that if the accident takes place at the last moment $t = T$ of the flight (including landing) and the workload G is not infinitely large (say, because the environmental conditions are reasonably favorable and the navigation instrumentation and other hardware are adequate and reliable), then both probabilities $P_{0.5}(F)$ and $P_{1.0}(F)$ are zero, and no casualty could possibly occur: it is simply too late in the flight for a mishap to happen. As mentioned in the Introduction section, in the current treatment we do not directly address the end-of-flight (landing) situation. It is noteworthy that such a situation could be indirectly considered within the framework of the introduced formalism, in a tentative fashion, by simply adequately increasing the hypothetical MWL level in the en route conditions: i.e., by introducing a certain margin of safety. Another, perhaps better-substantiated, approach is to consider the contributions of the en route and descending-and-landing situations by introducing a cumulative EVD PDF function that would account for (with an emphasis on the landing, rather than en route, conditions) the contributions of both en route and landing conditions to the cumulative probability of a casualty.

If the accident takes place at the initial moment $t = 0$ of time, i.e., at the very beginning of the flight, then formulas (4) and (5) yield

$$P_{0.5}(F) = 1 - \exp\left[-\frac{G^2}{4G_0^2}\exp\left(-\frac{F^2}{F_0^2}\right)\right] \tag{6}$$

$$P_{1.0}(F) = 1 - \exp\left[-\frac{G^2}{G_0^2}\exp\left(-\frac{F^2}{F_0^2}\right)\right] \tag{7}$$

In such a situation, if the total MWL G is high and the HCF F is finite, the probabilities (6) and (7) are equal to one: the human failure will definitely take place and the aircraft casualty will certainly occur. However, if the total MWL G is low while the HCF F is significant, then the probabilities $P_{0.5}(F)$ and $P_{1.0}(F)$ become zero: no human failure or an aircraft casualty are likely to occur.

D. Probability of a Casualty If One of the Pilots Becomes Incapacitated

No casualty could possibly occur if one of the following cases takes place:

1) None of the pilots fails to perform his/her duties during the entire flight.

2) The captain fails to perform his/her duties, but the first officer takes over completely and successfully the operation of the aircraft.

3) The first officer fails to perform his/her duties, but the captain takes over completely and successfully the operation of the aircraft.

The probability of the first event is obviously $(1 - P_{0.5})^2$. The probabilities of the second and the third events are the same and are equal to $P_{0.5}(1 - P_{1.0})$. The probability of an accident-free flight is therefore

$$P = (1 - P_{0.5})^2 + 2P_{0.5}(1 - P_{1.0}) = 1 + P_{0.5}(P_{0.5} - 2P_{1.0}) \tag{8}$$

and the probability of a casualty is

$$Q = P_{0.5}(2P_{1.0} - P_{0.5}) \tag{9}$$

From Eqs. (2) and (3) we obtain

$$P_{1.0}(F) = 1 - [1 - P_{0.5}(F)]^4 \tag{10}$$

$$P_{0.5}(F) = 1 - \sqrt[4]{1 - P_{1.0}(F)} \tag{11}$$

If none of the pilots fails, i.e., $P_{0.5}(F) = P_{1.0}(F) = 0$, no accident could possibly occur: $Q = 0$. If one of the pilots is unable to cope even with the half of the MWL, i.e., when $P_{0.5}(F) = 1$, then, as follows from formula (10), he/she will not be able to cope with the total workload either, i.e., $P_{0.1}(F) = 1$ as well, and the casualty becomes inevitable: $Q = 1$. When the probability $P_{0.5}(F)$ is small, the probability $P_{1.0}(F)$ is also small and, as evident from Eq. (10), can be found as $P_{1.0}(F) = 4P_{0.5}(F)$, so that the probability of the casualty in this case is $Q = 7P_{0.5}^2 = \frac{7}{16}P_{1.0}^2 \approx 0.4375P_{1.0}^2$. Thus, the probability of a casualty is very low if the probability that a pilot fails

Table 1 Probabilities $P_{0.5}(F)$ and Q as functions of probability $P_{1.0}(F)$

$P_{1.0}(F)$	$P_{0.5}(F)$	Q
0	0	0
0.000001	2.5E − 7	4.375000E − 12
0.00001	2.5E − 6	4.375000E − 11
0.0001	2.5E − 5	1.750000E − 8
0.0005	0.000125	1.093750E − 7
0.0010	0.000250	4.375000E − 7
0.0050	0.001252	1.095250E − 5
0.0500	0.012741	0.00111177
0.1000	0.025996	0.00452341
0.2000	0.054258	0.01875927
0.3000	0.085309	0.04390777
0.4000	0.119888	0.08153727
0.5000	0.159103	0.13378923
0.6000	0.204729	0.20376084
0.7000	0.259917	0.29632695
0.8000	0.331260	0.42028281
0.8500	0.377667	0.49939776
0.9000	0.437659	0.59624080
0.9500	0.527129	0.72368012
1.0000	1.000000	1.00000000

to perform his/her duties in ordinary conditions is small. This intuitively obvious circumstance, known from the avionic practice, is quantified by the above reasoning.

The probabilities $P_{0.5}(F)$ and Q are computed as functions of the probability $P_{1.0}(F)$ in Table 1. The following conclusions could be drawn from the computed data:

1) The probability $P_{1.0}(F)$ that the pilot fails to cope with the total workload is always higher than the probability $P_{0.5}(F)$ of failure to perform his/her normal duties. The Table 1 data quantify this intuitively obvious fact.

2) The good news, though, is that the probability Q of a casualty is, in general, substantially lower than the probability $P_{1.0}(F)$ that one of the pilots becomes unable to cope with the total workload. This is especially true when the probability $P_{1.0}(F)$ is low. No wonder that there were no casualties in the recently reported accidents when one of the two pilots became incapacitated during the flight: 18 June 2009 Continental flight 61 from Brussels to Newark; 24 February 2008 GB Airways flight BA6826 from Manchester to Cypress; or 23 January 2007 Continental flight 1838 from Houston to Puerto Vallarta. It is only when the likelihood of the inability of the PIC to cope with the entire workload is next to one that the likelihood of the casualty also becomes close to 1. For example, if one wants to keep the probability of a casualty below, say, $10^{-5} = 0.001\%$, then the probability $P_{1.0}(F)$ that one of the pilots will be unable to cope, if necessary, with the entire workload should be kept below 0.5%. If the latter probability is as high as 10%, then the probability of a casualty becomes as high as 0.45%.

3) Formulas (4) and (5) and the Table 1 data indicate that the probability Q of a casualty is lower than the probability $P_{0.5}(F)$ of failure of one of the pilots to cope with one-half of the workload if the probability $P_{1.0}$ of his/her failure to cope with the entire workload is below $P_{1.0} = 1 - \frac{1}{2\sqrt[3]{2}} = 0.6031$. The probability Q of a casualty becomes higher than the probability $P_{0.5}(F)$ of failure of one of the pilots to cope with one-half of the workload if the probability $P_{1.0}$ of his/her failure to cope with the entire workload is higher than the above (rather high and, hence, unrealistic) number. It goes without saying that there is always a strong incentive to make the probability of failure of each pilot at the ordinary flight conditions as low as possible. The Table 1 data quantify this intuitively obvious conclusion.

E. Required Extraordinary (Offnormal) Versus Ordinary (Normal) HCF Level

Let us assess, based on the distribution (1), how the HCF F should change, so that the probabilities $P_{1.0}$ and Q are still maintained low, despite the occurrence of an accident. From Eq. (5) we find

$$\frac{F}{F_0} = \sqrt{-\ln\left[-\frac{T}{T-t}\frac{G_0^2}{G^2}\ln(1-P_{1.0})\right]} \tag{12}$$

The worst-case scenario takes place when the accident occurs at the middle of the flight, when there not an appreciable incentive for turning back, and the PIC has to operate the aircraft by himself/herself for the longest time. Let us assume that the accident took place at the moment t of time, for which $t/T = 0.5$, and that after the accident has happened, the MWL G is twice as high as the ordinary (specified) workload G_0. Then formula (12) yields

$$\frac{F}{F_0} = \sqrt{-\ln\left[-\frac{1}{2}\ln(1-P_{1.0})\right]} \tag{13}$$

If, for instance, one requires that the probability Q of the casualty does not exceed $Q = 10^{-5}$, then, as follows from Table 1 data, the probability $P_{1.0}$ should be kept below $P_{1.0} = 0.005 = 0.5\%$, and formula (13) yields $F/F_0 = 2.4472$. Hence, the requirements for the HCF (whatever the definition and structure of this factor are agreed upon and whatever corresponding figures of merit might be accepted) are such that the extraordinary (offnormal) HCF should be a factor of 2.45 larger than the ordinary (normal) value of this factor. In other words, the pilot should be trained (e.g., on a flight simulator) in such a way that he/she would exhibit/manifest the necessary skills and capabilities in offnormal situations, if/when they occur, by a factor of 2.45 larger than in normal conditions. If one requires that the probability of failure does not exceed a number as low as $Q = 10^{-7}$, then the required F/F_0 ratio is somewhat higher: $F/F_0 = 2.8799$. As evident from these data, even such a considerable change in the level of the hazardous condition did not lead to a significant change in the requirements for the HCF level; a threefold increase in what seems to be acceptable in normal flight conditions is also sufficient for a satisfactory performance of the pilot in a hazardous situation. The practical conclusion from this result is that the existing methods of training skilled and experienced pilots on flight simulators are most likely adequate; no dramatic increase in the overload during training is necessary.

Let us now consider a hypothetical situation of when the accident took place at the initial moment of time, but the PIC and the air traffic controller nonetheless decided to not interrupt the schedule and to continue the flight. How risky might such a decision be? In this case, formula (12) yields

$$\frac{F}{F_0} = \sqrt{-\ln\left[-\frac{1}{4}\ln(1-P_{1.0})\right]} \tag{14}$$

For probabilities $Q = 10^{-5}$ and 10^{-7} of the casualty, we obtain $F/F_0 = 2.5850$ and 2.9978, respectively. Hence, the time of an accident has a relatively small effect on the required increase in the level of the offnormal HCF, so that the threefold increase compared with normal conditions seems to be still adequate. Thus, the hypothetical decision to continue the flight, instead of returning to the airport of departure, might not be completely unjustifiable.

We would like to point out that the above factors of the increased workload during training, although they are a logical output of the employed probabilistic formalism, might have different interpretation in today's practice, in which skilled and qualified pilots are trained to the best of the ability of the existing simulators and personnel involved. The authors of this paper simply state that based on the obtained probabilistic information, the workload during training (whatever its level) does not have to be infinitely and indefinitely high, but could be just/only threefold more extensive than the regular MWL. It would be extremely useful, of course, if it would be possible to establish a quantitative measure of how high the typical MWL level is during training (i.e., when the pilots are prepared to operate effectively both in ordinary and extraordinary conditions) in comparison with ordinary flight conditions. This effort is beyond the scope of our paper, however. It would be highly

Table 2 Computed Q_* vs t/T

	t/T					
Q	0	0.2	0.4	0.6	0.8	1.0
0	0	0	0	0	0	0
E − 7	E − 7	8E − 8	6E − 8	4E − 8	2E − 8	0
E − 5	E − 5	8E − 6	6E − 6	4E − 6	2E − 6	0
E − 3	E − 3	8E − 4	6E − 4	4E − 4	2E − 4	0
0.01	0.01	0.008	0.006	0.004	0.002	0
0.04	0.04	0.0323	0.0244	0.0164	0.00826	0
0.08	0.08	0.0650	0.0522	0.0336	0.0171	0
0.10	0.10	0.0816	0.0625	0.0420	0.0217	0
0.20	0.20	0.1667	0.1304	0.0909	0.0476	0
0.40	0.40	0.3478	0.2857	0.2105	0.1176	0
0.60	0.60	0.5455	0.4737	0.3750	0.2308	0
0.80	0.80	0.7619	0.7059	0.6154	0.4444	0
1.00	1.00	1.00	1.00	1.00	1.00	——

desirable, of course, to carry out such an analysis on a flight simulator.

F. Effect of the Time of an Accident on Its Likelihood

The objective of the analysis carried out in this section is to assess the effect of the actual time of operation on the likelihood of a casualty.

Assume that the probability Q of a possible casualty is evenly distributed over the time T of the flight and that no casualty has actually occurred during the initial time t of the flight. What is the probability Q_* that the casualty will occur during the remaining time $T - t$?

Two events have to take place for the accident to occur during the time $T - t$: 1) the accident should not take place during the time t and 2) the accident has to occur during the time $T - t$. The probability that the casualty occurs during the time t is $Q(t/T)$. The probability that the casualty occurs during the remaining time $T - t$, provided that it did not occur during the time t, is $(1 - Q(t/T))Q_*$. The probability Q that the casualty occurs during the total time T can be found as

$$Q = Q\frac{t}{T} + \left(1 - Q\frac{t}{T}\right)Q_* \tag{15}$$

Hence, the probability Q_* that the casualty will occur during the remaining time $T - t$ is related to the probability Q of the occurrence of the accident during the entire flight (mission) as follows:

$$Q_* = Q\left[\left(1 - \frac{t}{T}\right)\Big/\left(1 - Q\frac{t}{T}\right)\right] \tag{16}$$

Hence,

$$Q = Q_*\Big/\left(1 - \frac{(1 - Q_*)t}{T}\right) \tag{17}$$

The computed Q_* values vs the time ratio t/T are given in Table 2. The following conclusions could be drawn from the computed data:

1) The probability Q_* that the casualty occurs during the remaining time $T - t$ of the flight if it did not occur during the time t is always smaller than the specified probability Q of the casualty occurrence during the total flight time T and decreases with an increase in the total time T of the flight.

2) At the last moment of time $t = T$ the probability Q_* is zero, no matter how high the probability Q is, unless the latter probability is equal to one.

3) The probability Q_* that the accident will occur during the remaining time $T - t$ increases with an increase in the specified probability Q. The two probabilities coincide at the initial moment of time $t = 0$.

4) If one wants to keep the probability Q_* at a sufficiently low level, then he/she should also keep the specified probability Q at a low level.

The above intuitively more-or-less-obvious conclusions are quantified by the Table 2 data.

III. Future Work

The authors realize that the PRM approach (which has proven to be successful in numerous engineering applications, particularly in reliability problems, including aviation technologies [1]) might not be accepted easily by some psychologists. Many of them may feel that the problem is too complex to lend itself to any type of quantification and might challenge the approach. With this in mind we would like to suggest several possible next steps (future work) that could/should be conducted using flight simulators, when necessary, to correlate the distribution (1) and its possible modifications with the existing practice and to make this distribution applicable for the evaluation of the roles of the MWL and HCF in particular navigation situations. Aviation psychologists do not normally measure HCF as a single unitary quantity. They might estimate the human ability to handle stress or test his/her reaction time or his/her ability to visually detect targets out the window, etc. These are all separate parameters that improve the pilot's ability to handle workload. It is important, however, that all these parameters (as well as some more permanent factors like the pilot's qualifications, general professional experience and skills, performance sustainability, ability to concentrate, ability to make adequate and prudent decisions in conditions of uncertainty, etc.) are also considered in a unified HCF. It is mandatory, of course, that such a unified HCF is measured in the same units as is the MWL; otherwise, the demand-capacity model could not be used. These units could be particularly dimensionless, but should be established for a particular mission or task in advance. Other, perhaps less challenging, tasks might include the following:

1) Test to evaluate the effect of the fatigue state of the pilot on the effectiveness of his/her performance: there are cognitive test methodologies that can assess alertness.

2) Carry out continuous MWL measurements using subjective and/or psychophysiological measures.

3) Assess the role of the aircraft type and the effectiveness of automation; more automation will make the pilot's job easier, in most cases, but might not be always available or affordable.

4) Evaluate the role of weather conditions that might affect the MWL and might have an effect on the HCF as well.

5) Assess the role of the phase of flight. Since descent and landing are characterized by the highest level of MWL, formula (1) should be applied and verified for these conditions. The authors believe that it could be indeed applicable to such conditions, although we did not consider them specifically and directly in this paper. Particularly, complexity of the airport and air traffic situation might have an effect on the MWL; more complexity certainly means more MWL for the pilot to manage.

6) Categorize the types of errors/outcomes (again, typical and possible errors, not mistakes or blunders: these are beyond any PRM analysis) that might occur. One should determine ahead of time the kinds of deviations of normal conditions and the kinds of errors/outcomes in which he/she is interested. Catastrophic loss of an aircraft usually results from a series of failures: deviations from normal conditions that might lead to a casualty or an unrecoverable situation. There was probably no reported loss of a commercial aircraft because one of the pilots was incapacitated, and our analysis has indicated that. Indeed, such an outcome would be rather unlikely, unless the pilot in charge is very bad and the probability that he/she fails even in normal operation conditions is next to one (see Table 1). In this connection we would like to point out again that the addressed example is just an illustration of one of the possible applications of the basic relationship (1). This relationship might have many more applications in vehicular technology and, as far as the aviation industry is concerned, might be applicable (after appropriate modification and generalization) to address not only (less critical) en route situations, but also landing situations.

7) Use the model to compare the performance of different pilots for different MWL levels. Of course, even a significant deviation from normal conditions does not necessarily lead to a casualty, and our model is able to quantify this circumstance. Additional insight is needed, however, to correctly design and adequately interpret the results of the tests in a flight simulator. In this connection it would be interesting to compare the accelerated life test and highly accelerated life tests in hardware electronics (see, for instance, [23]) with what could be expected from the flight simulation tests.

8) Evaluate the effects of the assistance of the air traffic controller and airline flight dispatcher who would help the flight crew if one of the pilots became incapacitated.

Note that application of the Delphi method (see, for instance, [19]) could be quite useful to shed light on the challenges and possible pitfalls in the problems in question.

IV. Conclusions

A double-exponential probability distribution function (PDF) of the extreme-value-distribution (EVD) type is introduced to characterize and to quantify the likelihood of a human failure to perform his/her duties when operating a vehicle (a car, an aircraft, a boat, etc.). This function is applied to a particular safety-in-air situation when one of the two pilots becomes incapacitated for one reason or another at a certain moment of time in the flight and, because of that, the other pilot has to cope with a considerably higher workload, as compared with regular flight conditions. The probability of this event is assessed as a function of the HCF.

Methods of the classical probability theory are shown that could be employed to quantify the role of the human factor in the situation in question. Further research, refinement, and validation would be needed before the model could see practical application. The suggested model, after an appropriate sensitivity analysis is carried out, might be used particularly when developing guidelines for personnel training and/or when there is a need to decide if the existing navigation instrumentation is adequate in extraordinary safety-in-air situations or if additional and/or more advanced equipment should be developed and installed.

The initial numerical data based on the suggested model make physical sense and are in satisfactory (qualitative) agreement with the existing practice. In conclusion, it is important to relate the model expressed by the basic equation (1) to the existing practice and to review the existing practice from the standpoint of the generally consistent model expressed by Eq. (1).

Acknowledgments

The authors acknowledge, with thanks, a useful discussion with Captain Rob Koteskey and support of Heinz Erzberger, NASA Ames Research Center.

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