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HUMAN-IN-THE-LOOP:
LIKELIHOOD OF A VEHICULAR MISSION SUCCESS AND SAFETY

A double-exponential probability distribution function (DEPDF) of the extreme value distribution (EVD) type is introduced to quantify the likelihood of the human failure to perform his/her duties, when operating a vehicle: an aircraft, a spacecraft, a boat, a helicopter, a railroad vehicle, etc. Such a failure, if any, is attributed to the insufficient human capacity factor (HCF), when there is a need to cope with a high (extraordinary, off-normal) level mental-workload (MWL). A possible application of the suggested DEPDF is a situation when an imperfect human, an imperfect equipment/instrumentation, and an uncertain-and-possibly-harsh environment contribute jointly to the likelihood of a vehicular mission failure and/or insufficient safety. While the human's performance is characterized by the DEPDF, the performance of the equipment (instrumentation), which includes, in our analysis, the performance of both the hardware and the software, is characterized by the Weibull distribution, and the role of the uncertain environment is considered by the probability of the occurrence of harsh environmental conditions of the anticipated level of severity. We believe that the suggested MWL/HCF model and its pos-sible modifications and generalizations, can be helpful, after appropriate sensitivity analyses are carried out, when developing guidelines for personnel selection and training; when choosing the appropriate simulation conditions; and/or when there is a need to decide, if the existing levels of automation and the employed equipment (instrumentation) are adequate in off-normal, but not impossible, situations. If not, additional and/or more advanced and perhaps more expensive equipment or instrumentation should be developed and installed.

Keywords: *double-exponential probability distribution function, human capacity factor, mental-workload level, human failure, safe operation of the vehicle.*

Функция двойного экспоненциального распределения вероятностей (ДЭРВ) типа распределения экстремальных значений (РЭЗ) вводится для количественной оценки вероятности отказа оператора (человека) при выполнении им обязанностей по управлению работой транспортного средства: самолетом, космическим кораблем, судном, вертолетом, железнодорожным локомотивом и т.д. Появление такого отказа, объясняется недостаточным фактором человеческого потенциала (ФЧП), в том случае когда существует необходимость справиться с высоким (экстраординарным) уровнем психической нагрузки (УПН).

Возможным применением предложенного ДЭРВ является ситуация, когда неподготовленный человек, несовершенное оборудование / приборы, а также неизвестное и возможно суровое состояние окружающей среды по совокупности вероятностей способствуют провалу миссии транспортного средства и / или недостаточной её безопасности. Предложенная УПН / ФЧП модель и ее возможные модификации и обобщения, после соответствующих анализов чувствительности, могут быть использованы при разработке руководящих принципов для отбора и обучения персонала; при выборе надлежащих условий моделирования; и / или когда возникает необходимость решить, являются ли существующие уровни автоматизации и применяемое оборудование (приборы) достаточными в экстремальной, но возможной ситуации. В противном случае должно быть разработано и установлено дополнительное и / или более передовое и, возможно, более дорогое оборудование или приборы.

Ключевые слова: *Функция двойного экспоненциального распределения вероятностей, фактор человеческого потенциала, уровень психической нагрузки, человеческий фактор, обеспечение безопасности работы транспортного средства.*

Функція подвійного експоненціального розподілу ймовірностей (ДЕРЙ) типу розподілу екстремальних значень (РЕЗ) вводиться для кількісної оцінки імовірності відмови оператора (людини) при виконанні ним обов'язків по управлінню роботою транспортного засобу: літака, космічного корабля, судна, вертольота, залізничного локомотива і т.і., Поява такої відмови, пояснюється недостатнім фактором людського потенціалу (ФЛП), в тому випадку коли існує необхідність впоратися з високим (екстраординарним) рівнем психічного навантаження (РПН). Можливим застосуванням запропонованого ДЕРЙ є ситуація, коли непідготовлена людина, недосконале обладнання / прилади, а також невідомий і можливо суворий стан довкілля за сукупністю ймовірностей сприяють провалу місії транспортного засобу та / або недостатньої її безпеки. Запропонована РПН / ФЛП модель її можливі модифікації та узагальнення, після відповідних аналізів чутливості, можуть бути використані при розробці ке-рівних принципів для відбору та навчання персоналу; при виборі належних умов моделювання; та / або коли виникає необхідність вирішити, чи є існуючі рівні автоматизації і застосоване обладнання (прилади) достатніми в екстремальній, але можливій ситуації. В іншому випадку має бути розроблено та встановлено додаткове та / або більш передове і, можливо, більш дороге обладнання або прилади.

Ключові слова: *Функція подвійного експоненціального розподілу ймовірностей, фактор людського потенціалу, рівень психічного навантаження, людський фактор, забезпечення безпеки роботи транспорт-ного засобу.*

Introduction. Considerable improvements in various vehicular (aerospace, maritime, automotive, railroad, etc.) technologies can be achieved through better ergonomics, better work environment, and other means that directly affect human behavior. There is also an opportunity (potential) for a further reduction in vehicular casualties through better understanding the role that various uncertainties play in the designer's and 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 as the most crucial part) of the complex man-instrumentation-equipment-vehicle-environment system, one could improve dramatically the human performance, to predict and, if needed, minimize and even specify the probability of the occurrence of a mishap.

In the analysis that follows we introduce a double-exponential probability distribution function (DEPDF) of the extreme value distribution (EVD) type [1-5] to quantify the likelihood of a human failure to perform his/her duties, when operating a vehicle. We consider, as a suitable illustration, a situation when imperfect human, imperfect equipment and an uncertain-and-often-harsh environment contribute jointly to a possible failure of a mission or to a likelihood of a casualty. We believe that the suggested MWL/HCF concept and its generalizations, after the appropriate sensitivity analyses are carried out, can be helpful when developing guidelines for personnel ***selection and*** 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 existing navigation instrumentation and equipment are adequate in extraordinary (off-normal) situations. If not, additional or more advanced and perhaps more expensive instrumentation and equipment should be considered, developed and installed.

Our analysis is, in effect, an attempt to quantify, on the probabilistic basis, using analytical («mathematical») probabilistic risk management (PRM) techniques, the role that the human plays, in terms of his/her ability (capacity) to cope with a mental overload. Using an analogy from the reliability engineering field and particularly with the «stress-strength» interference model (see, e.g., [1]), the MWL could be viewed as a certain «demand» («stress»), while the HCF − as a «capacity» («strength»). In our DEPDF model we combine the demand and the capacity factors within the same probability-of-non-failure distribution. It is the relative levels of the (steady-state or time-dependent) MWL and HCF that determine in our concept the likelihood of a mission success and safety.

The MWL («demand») depends on the operational conditions and the complexity of the mission, i.e., has to do with the significance of the general task [4-25]. The MWL is directly affected by the challenges that a navigator faces, when he/she has to control the vehicle in a complex, heterogeneous, multitask, and often uncertain and harsh 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 that has to do with the attention and task management. As to the HCF («capacity»), 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 ope-rate 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 [3], etc.

In this analysis we assume that, while the MWL and the HCF are random variables, the most likely («specified») MWL and HCF values in a particular mission and for a particular individual are deterministic parameters that are known (established, predetermined) in advance. This could be done particularly by employing accelerated testing on flight simulator equipment. Testing should continue until an anticipated failure (whatever the definition) occurs and the mean-time-to-failure (MTTF) should be measured for the selected group of typical (experienced) navigators. Such failure-oriented-accelerated testing («testing-to-fail»), as opposite to «testing-to-pass», known in reliability engineering as qualification testing [26-28], is viewed to be analogous to the acce-lerated life testing (ALT) in electronics and photonics [26]. Although the evaluation of the most likely MWL and HCF is beyond the scope of the present analysis, a brief discussion is put nonetheless in Sections ***IX*** and ***X*** on how some factors affecting the specified MWL and HCF are, or might be, approached in the today's aviation psychology practice.

It is noteworthy that the ability to evaluate the «absolute» level of the MWL, important as it might be for non-comparative evaluations, is less critical in this study, which is aimed at the comparative assessments of the likelihood of a casualty in normal and off-normal situations. We would like to point out also that we do not intend in this paper to come up with any accurate, complete, ready-to-go, «off-the-shelf»-type methodology, in which all the i's are dotted and all the t's are crossed. Our intent is just to illustrate how the PRM methods and approaches could be effectively employed to quantify the role of the human factor, when both human performance and equipment (instrumentation) reliability contribute to the likelihood of a mishap. We believe that the taken approach, with the appropriate modifications and generalizations, is applicable to many other situations, not necessarily in the vehicular domain, when a human encounters an uncertain environment and/or a hazardous situation and/or interacts with never perfect hardware and software.

I. Double-Exponential EVD-Type Probability Distribution Function of the Human Non-Failure. We assume in this analysis that the steady-state probability $P^h(F,G)$ of the navigator's non-failure, when the vehicle is operated in off-normal (extraordinary) conditions, is distributed in accordance with the following double-exponential law of the extreme-value-distribution (EVD) type [1-5] (1)

$$P^h(F,G) = P_0 \exp\left[\left(1-\frac{G^2}{G_0^2}\right)\exp\left(1-\frac{F^2}{F_0^2}\right)\right]. \quad (1)$$

Table 1

Calculated $\overline{P} = P^h(F,G)/P_0$ ratios of the probability $P^h(F,G)$ of human non-failure in off-normal conditions to the probability P_0 of non-failure in normal conditions

G^2/G_0^2	1	2	3	4
F^2/F_0^2	xxxxx	xxxxxx	xxxxxx	xxxxxx
1	1	0.3679	0.1353	0.0498
2	1	0.6922	0.4791	0.3317
3	1	0.8734	0.7629	0.6663
4	1	0.9514	0.9052	0.8613
5	1	0.9819	0.9640	0.9465
8	1	0.9991	0.9982	0.9978
10	1	0.9999	0.9998	0.9996
∞	1	1	1	1

Table 1 continuation

G^2/G_0^2	5	8	10	∞
F^2/F_0^2	xxxxxx	xxxxxx	xxxxxx	xxxxxx
1	0.0183	9.1188E-4	1.234E-4	0
2	0.2296	0.0761	0.0365	0
3	0.5820	o.3878	0.2958	0
4	0.8194	0.7057	0.6389	0
5	0.9294	0.8797	0.8480	0
8	0.9964	0.9936	0.9918	2.5E-40
10	0.9995	0.9991	0.9989	4.4E-6
∞	1	1	1	1

Here P_0 is the probability of the non-failure of the human performance for the specified (normal) mental workload (MWL) level, when $G = G_0$; G_0 is the most likely (normal, specified) MWL (i.e., MWL in ordinary operation conditions); $G \geq G_0$ is the actual (elevated, off-normal) MWL; $F = F_0$ is the most likely (normal, specified) HCF, i.e., the HCF in ordinary (normal) conditions; $F \geq F_0$ is the actual HCF exhibited at the extraordinary (off-normal) conditions. The P_0 level of the probability of the human performance non-failure in normal conditions, i.e., in the case of a human with a normal (most likely) level of the HCF (a performer with ordinary skills in the profession), should be established beforehand, as a function of the G_0 level, i.e., when the HCF $F = F_0$. This could be done, e.g., by conducting testing and measurements on a flight simulator. The calculated ratios (2) of the probability of human non-failure in off-normal conditions to the probability of non-failure in normal conditions are shown in Table 1.

$$\overline{P} = \frac{P^h(F,G)}{P_0} = \exp\left[\left(1 - \frac{G^2}{G_0^2}\right)\exp\left(1 - \frac{F^2}{F_0^2}\right)\right]. \qquad (2)$$

The following conclusions are drawn from the calculated data:

1. At normal MWL level $(G = G_0)$ and/or at an extraordinarily (exceptionally) high HCF level $(F \to \infty)$ the probability of human non-failure is close to 100 %.

2. The probabilities of human non–failure in off-normal conditions are always lower than the probabilities of non-failure in normal conditions. This obvious fact is quantified by the calculated data.

3. If the MWL is exceptionally high, the human will definitely fail, no matter how high his/her HCF is.

4. If the HCF is high, even a significant MWL has a small effect on the probability of non-failure, unless this workload is exceptionally large.

5. The probability of non–failure decreases with an increase in the MWL (especially for relatively low MWL levels) and increases with an increase in the HCF (especially for relatively low HCF levels). This intuitively obvious fact is quantified by the calculated data.

6. For high HCFs the increase in the MWL level has a much smaller effect on the probabilities of non-failure than for relatively low HCFs.

All these conclusions make physical sense.

The Table 1 data show also that the increase in the F / F_0 ratio and in the G / G_0 ratio above the 3.0 value has a small effect on the probability of non-failure. This means particularly that the navigator (pilot) does not have to be trained for an extraordinarily high MWL and does not have to be trained by a factor higher than 3.0 compared to a navigator of ordinary capacity (skills, qualification). In other words, a pilot does not have to be a superman to successfully cope with a high level MWL, but still has to be trained in such a way that, when there is a need, he/she would be able to cope with a MWL by a factor of 3.0 higher than the normal level, and his/her HCF should be by a factor of 3.0 higher than what is expected of the same person in ordinary (normal) conditions.

From (2) we find, by differentiation (3)

$$\frac{d\overline{P}}{dG} = -\frac{2H}{G}\frac{G^2}{G^2 - G_0^2}, \tag{3}$$

where $H = -\overline{P}\ln\overline{P}$ is the entropy (see, e.g., [1]) of the distribution of the relative probability of the human non-failure in extraordinary (off-normal) conditions of operation as compared to ordinary (normal) conditions. At the MWL levels close to the normal level, the change in the relative probability of non-failure with the increase in the load level is significant. In another extreme case, when $G \succ\succ G_0$, we have (4)

$$\frac{d\overline{P}}{dG} = -\frac{2H}{G}. \tag{4}$$

This formula explains the physical meaning of the DEPDF (1): the change in the probability of non-failure with the change in the level of the MWL is proportional, for large enough MWL levels, to the uncertainty level (entropy of the distribution of this probability) and is inversely proportional to the MWL level. The right part of the formula (4) could be viewed as a kind of a coefficient of variation (COV), where the role of the uncertainty level in the numerator is played by the entropy, rather than by the standard deviation, and the role of the stress (loading) level in the denominator is played by the MWL level, rather than by the mean value of the random characteristic of interest.

II. Likelihood of the Vehicular Mission Success-and-Safety. The success (failure) of a vehicular mission could be time dependent and, in addition, could have different probabilities of success at different stages (segments). Let, e.g., the mission of interest consists of n consecutive segments ($i = 1,2,...,n$) that are characterized by different probabilities, q_i, of occurrence of a particular harsh environment or by other extraordinary conditions during the fulfillment of the i -th segment of the mission; by different durations, T_i, of these segments; and by different failure rates, λ_i^e, of the equipment and instrumentation. These failure rates may or may not depend on the environmental conditions, but could be affected by aging, degradation and other time-dependent causes.

In the simplified example below we assume that the combined input of the hardware and the software, as far as the failure rate of the equipment and instrumentation is concerned, is evaluated beforehand and is adequately reflected by the appropriate failure rate λ_i^e (failure rate of the equipment) values. These values could be either determined from the vendor specifications or could be obtained based on the specially designed and conducted ALT and the subsequent predictive modeling [26].

The probability of the equipment non-failure at the moment t_i of time during the flight on the i -th segment, assuming that Weibull distribution is applicable, is

$$P_i^e = \exp\left[-\left(\lambda_i^e t_i\right)^{\beta_i^e}\right], \qquad (5)$$

where $0 \le t_i \le T_i$ is an arbitrary moment of time during the fulfillment of the mission on the i-th segment, and β_i^e is the shape parameter in the Weibull distribution. The distribution (5) is flexible: $\beta_i^e = 1$ leads to the exponential distribution; when $\beta_i^e = 2$, Rayleigh distribution takes place; by putting $\beta_i^e = 3$, one obtains a distribution that is close to the normal distribution.

We assume that the time–dependent probability of the human performance non-failure can be also represented in the form of Weibull distribution

$$P_i^h(t_i) = P_i^h(0)\exp\left[-\left(\lambda_i^h t_i\right)^{\beta_i^h}\right], \qquad (6)$$

where λ_i^h is the failure rate, β_i^h is the shape parameter and $P_i^h(0)$ is the probability of the human non-failure at the initial moment of time $t_i = 0$ of the given segment. When $t_i \to \infty$, the probability of non-failure (say, because of the human fatigue or other causes) tends to zero. The probability $P_i^h(0)$ can be assumed in the form (1), i.e. (7)

$$P_i^h(0) = P_0 \exp\left[\left(1-\frac{G_i^2}{G_0^2}\right)\exp\left(1-\frac{F_i^2}{F_0^2}\right)\right]. \qquad (7)$$

Then the probability of the mission failure at the i-th segment can be found as (8)

$$Q_i(t_i) = 1 - P_i^e(t_i)P_i^h(t_i). \qquad (8)$$

Since (9)

$$\sum_{i=1}^{n} q_i = 1. \qquad (9)$$

(condition of normalization), the overall probability of the mission failure can be determined as follows:

$$Q = \sum_{i=1}^{n} q_i Q_i(t_i) = 1 - \sum_{i=1}^{n} q_i P_i^e(t_i)P_i^h(t_i). \qquad (10)$$

This formula can be used for the assessment of the probability of the overall mission failure, as well as, if necessary, for specifying the failure rates and the HCF in such a way that the probability of failure, when a human is involved, would be sufficiently low and acceptable. It can be used also, if possible, to choose an alternative route in such a way that the set of the probabilities q_i brings the overall probability of failure of the mission to the acceptable level.

If at a certain segment of the fulfillment of the mission the human performance is not critical, then the corresponding probability $P_i^h(t_i)$ of human non-failure should be put equal to one. On the other hand, if there is confidence that the equipment (instrumentation) failure is not critical, or if there is a reason to believe that the probability of the equipment non-failure is considerably higher than the probability of the human non-failure, then it is the probability $P_i^e(t_i)$ that should be put equal to one. Finally, if one is confident that a certain level of the harsh environment will be certainly encountered during the fulfillment of the mission at the i -th segment of the route, then the corresponding probability q_i should be put equal to one.

III. Equipment (Instrumentation) Failure Rate. Failure rate of the equipment (instrumentation) should be established, of course, based on the reliability physics of the particular underlying phenomenon. Examine, as suitable examples, two typical situations.

1) If the possible failure of the vulnerable structural element of a particular piece of equipment, device or a subsystem could be attributed to an elevated temperature and stress, then the Bueche-Zhurkov law (11)

2)

$$\tau = \tau_0 \exp\left(\frac{U - \gamma\sigma}{kT}\right) \tag{11}$$

can be used to assess the mean-time-to-failure τ . In this formula, T is the absolute temperature, U is the activation energy, k is Boltzmann's constant, σ is the design stress (not necessarily mechanical) acting in the item of interest, and τ_0 and γ are empirical parameters that should be established (found) based on the specially designed and conducted ALTs. Actually, the activation energy U is also an empirical parameter, but, for various structural elements of silicon-based semiconductor electronic devices the activation energies have been determined and could be found in the reference literature [26]. The second term in the numerator of the formula (11) accounts for the reduction in the activation energy level in the presence of a stress. If stress is not considered, the formula (11) reduces to the well-known Boltzmann-Arrhenius equation. After the mean-time-to-failure τ is determined, the corresponding failure rate can be found as

$$\lambda = \frac{1}{\tau_0}\exp\left(-\frac{U - \gamma\sigma}{kT}\right) = \frac{Q_T}{\tau_0}, \tag{12}$$

where

$$Q_T = \exp\left(-\frac{U - \gamma\sigma}{kT}\right) \tag{13}$$

is the steady-state probability of failure in ordinary conditions, i.e., at the steady-state portion of the «bathtub curve».

3) If the possible failure is attributed, e.g., to random vibrations, then

the following Steinberg's formula can be used to assess the mean-time-to-failure

4)

$$\tau = C\sigma_r^{-m/2} \tag{14}$$

Here σ_r is the mechanical stress at the resonance frequency, and C and m are material (structural) parameters that can be established by acce lerated life testing. The formula (14) reflects an assumption that the mean-time to failure is determined, for the given material and structure, by the square root of the resonant stress. The failure rate is therefore

$$\lambda = \frac{1}{C}\sigma_r^{m/2}. \tag{15}$$

IV. Human Performance Failure Rate. By analogy with how the failure rate for a piece of electronic equipment is determined, one could use the condition (12) to establish an ALT relationship for the human performance. We view the process of testing and training of a human on a simulator as a sort of an ALT (failure oriented accelerated testing) setup for a vehicle operator. From (1) we have, for $F = F_0$, i.e., using patent law terminology, for a human of the ordinary skills in the vehicular «art», the following formula for the probability of non-failure, when a navigator is being tested or trained on a flight simulator

$$P^h(G) = P_0 \exp\left(1 - \frac{G^2}{G_0^2}\right). \tag{16}$$

Then the probability of failure is

$$Q_h(G) = 1 - P^h(G) = 1 - P_0 \exp\left(1 - \frac{G^2}{G_0^2}\right) \tag{17}$$

and

$$\tau = \frac{1}{\lambda} = \frac{\tau_0}{Q_h(G)} = \frac{\tau_0}{1 - P_0 \exp\left(1 - \frac{G^2}{G_0^2}\right)}. \tag{18}$$

This formula can be employed to run an ALT procedure on a simulator, using the elevated MWL level G as the stimulus factor, to the same extent as the elevated absolute temperature is used to accelerate failures in the relationship (11). The parameters G_0, τ_0 and P_0 should be viewed as empirical parameters that could be determined from the relationship (18) as a result of tes-ting at different MWL levels G for many individuals and evaluating the corresponding mean-time-to-failure τ. Note, that as far as steady-state condition is concerned, we use the simplest, exponential, distribution for the evaluation of the probability P_0, while in our general mission-success-and-safety concept, reflected by the equation (10), we use a more general and more flexible Weibull distribution.

Since there are three experimental parameters in the relationship (18) that have to be determined, one needs three independent equations to determine these parameters. If the tests on a simulator are being conducted for three groups of individuals at three MWL levels G_1, G_2, and G_3, and their performance is measured by recording three times-to-failure τ_1, τ_2, and τ_3, then the G_0 value can be obtained from the following transcendental equation

$$\left(1-\frac{\tau_1}{\tau_2}\right)\left[\exp\left(1-\frac{G_3^2}{G_0^2}\right)-\frac{\tau_2}{\tau_3}\exp\left(1-\frac{G_2^2}{G_0^2}\right)\right]- \\ -\left(1-\frac{\tau_2}{\tau_3}\right)\left[\exp\left(1-\frac{G_2^2}{G_0^2}\right)-\frac{\tau_1}{\tau_2}\exp\left(1-\frac{G_1^2}{G_0^2}\right)\right]=0 \tag{19}$$

One could easily check that this equation is always fulfilled for $G_1 = G_2 = G_3 = G_0$.

It is noteworthy that, as has been determined above on the basis of the Table 1 data, testing does not (and should not) be conducted for MWL levels essentially higher than three-fold higher than the normal MWL is, otherwise a «shift» in the mode of failure (i.e., misleading results) is likely. In other words, the accelerated test conditions should be indeed accelerated ones, and have to be reasonably high, but should not be unrealistically/unreasonably high. We are all still human, not superhuman, and, even an experienced, young, competent and well trained individual cannot cope with an exceptionally high workload.

After the normal (most likely) MWL G_0 is evaluated, the probability of non-failure at normal MWL conditions can be found as

$$P_0 = \frac{1-\frac{\tau_1}{\tau_2}}{\exp\left(1-\frac{G_2^2}{G_0^2}\right)-\frac{\tau_1}{\tau_2}\exp\left(1-\frac{G_1^2}{G_0^2}\right)} = \\ = \frac{1-\frac{\tau_2}{\tau_3}}{\exp\left(1-\frac{G_3^2}{G_0^2}\right)-\frac{\tau_2}{\tau_3}\exp\left(1-\frac{G_2^2}{G_0^2}\right)} . \tag{20}$$

and the time τ_0 can be then determined, if necessary, as

$$\tau_0 = \tau_1\left[1-P_0\exp\left(1-\frac{G_1^2}{G_0^2}\right)\right] = \tau_2\left[1-P_0\exp\left(1-\frac{G_2^2}{G_0^2}\right)\right] = \\ = \tau_3\left[1-P_0\exp\left(1-\frac{G_3^2}{G_0^2}\right)\right] . \tag{21}$$

As evident from the formulas (19)-(21), the G_0 value can be found in a single way from the formula (19), the P_0 value can be found in two ways, using the formulas (20), and the τ_0 value can be found in three ways, using the formulas (21). This circumstance should be used to check the accuracy in determining these values. On the other hand, for the analysis based on the equation (10), only the P_0 value is needed. We would like to point out also that, although minimum three levels of the MWL are needed to determine the parameters G_0, τ_0 and P_0, it is advisable that tests at many more MWL levels (still within the range $\frac{G}{G_0} = 1-3$) are conducted, so that the accuracy in the prediction could be assessed. After the parameters G_0, τ_0 and P_0 are found, the failure rate can be determined as a function of the MWL level from the formula (18)

$$\lambda = \frac{1}{\tau_0}\left[1 - P_0 \exp\left(1 - \frac{G^2}{G_0^2}\right)\right]. \tag{22}$$

The nominal (normal, ordinary, specified) failure rate is therefore

$$\lambda = \frac{1-P_0}{\tau_0}. \tag{23}$$

V. Weibull Law. We use the Weibull law to evaluate the time effect (aging, degradation) on the performance of both the equipment (instrumentation), considering the combined effect of the hardware and software, and the «human-in-the-loop». It is a two-parametric distribution with the probability distribution function

$$F(t) = e^{-(\lambda t)^{\beta}}, \tag{24}$$

where the failure rate λ is related to the scale parameter η of the distribution as $\eta = \frac{1}{\lambda}$, and the mean-time-to-failure $\bar{t}$ and the standard deviation σ_t of the time-to-failure t can be found as

$$\bar{t} = \eta\Gamma\left(1+\frac{1}{\beta}\right), \sigma_t = \eta\sqrt{\Gamma\left(1+\frac{2}{\beta}\right) - \Gamma^2\left(1+\frac{1}{\beta}\right)}. \tag{25}$$

Here

$$\Gamma(\alpha) = \int_0^{\infty} x^{\alpha-1} e^{-x} dx \tag{26}$$

is the gamma-function. The probability density distribution function can be obtained, if needed, from (24) by differentiation

$$f(t) = \lambda\beta(\lambda t)^{\beta-1} e^{-(\lambda t)^{\beta}}. \tag{27}$$

VI. Numerical Example. Let, for instance, the duration of a particular vehicular mission be 24 hours, and the vehicle spends equal times at each of the 6 segments (so that $t_i = 4$ hours at the end of each segment), the failure rates of the equipment and the human performance are independent of the environmental conditions and are $\lambda = 8x10^{-4}$ 1/hour, the shape parameter in the Weibull distribution in both cases is $\beta = 2$ (Rayleigh distribution), the HCF ratio $\frac{F^2}{F_0^2}$ is $\frac{F^2}{F_0^2} = 8$ (so that $\frac{F}{F_0} = 2.828$), the probability of human non-failure at ordinary conditions is $P_0 = 0.9900$, and the MWL G_i^2 / G_0^2 ratios are given vs. the probability q_i of occurrence of the environmental conditions in Table 2.

The Table 2 data presumes that about 95% of the mission time occurs in ordinary conditions. The computations of the probabilities of interest are also carried out in Table 2. We obtain

$$P_i^e = \exp[-(\lambda t_i)^2] = \exp[-(8x10^{-4}x4)^2] = 0.99999,$$
$$P_i^h = P_0 \overline{P}_i \exp[-(\lambda t_i)^2] = 0.9900x0.99999\overline{P}_i = 0.99\overline{P}_i$$

and

$$\sum_{i=1}^{n} q_i P_i^e(t_i) P_i^h(t_i) = 0.9900,$$

which is the probability of the mission non-failure. The overall probability of mission failure is therefore

$$Q = 1 - \sum_{i=1}^{n} q_i P_i^e(t_i) P_i^h(t_i) = 1 - 0.9900 = 0.01 = 1\%.$$

VII. Imperfect Human vs. Imperfect Instrumentation: Short-Term Predictions. The concept based on the formula (10) and addressed in Sections III-VII is suitable for the design of the hardware and the software, for making long-term assessments and strategic decisions, and for planning a certain vehicular mission before this mission actually commences. There are, however, extraordinary situations, when the navigator has to make a decision on a short-term, some time even on an emergency, basis during the actual fulfillment of the mission. Here are several examples (problems) that have also to do with the application of PRM methods to quantify the combined effect of the human–equipment–environment interaction.

Table 2

Calculated probability of mission failure

i	1	2	3	4	5	6
q_i **%**	95.30	3.99	0.50	0.10	0.06	0.05
G_i/G_0	1	1.4142	1.7324	2.0000	2.2361	2.4495
$\overline{P}_i$	1	0.9991	0.9982	0.9978	0.9964	0.9955

P_i^h	0.9900	0.9891	0.9882	0.9878	0.9864	0.9855
$P_i^e P_i^h$	0.9900	0.9891	0.9882	0.9878	0.9864	0.9855
$q_i P_i^e P_i^h$	**0.9435**	**0.0395**	**0.0049**	**0.0010**	**0.0006**	**0.0005**

Problem №1. The probability that the particular environmental conditions will be detrimental for the vehicle safety (say, the probability of excee-ding a certain probability level) is *p*. The probability that these environmental conditions are detected by the available navigation equipment, adequately processed and delivered to the navigator in due time is p_1. But the navigator is not perfect either, and the probability that he/she misinterprets the obtained information from the navigation instrumentation is p_2. If this happens, the navigator can either launch a false alarm (take inappropriate and unnecessary corrective actions), or conclude that the weather conditions are acceptable and make inappropriate go-ahead decision. The navigator receives *n* messages from the navigation equipment during his watch. What is the probability that at least one of the messages is assessed incorrectly?

Solution. The hypotheses about a certain message are: H_1= the weather conditions are unacceptable, so that the corrective actions are necessary; H_2= the weather conditions are acceptable and therefore no corrective actions are needed. The probability that a message is misinterpreted is

$$P = p(1-p_1)+(1-p)p_2. \tag{28}$$

Then the probability that at least one message out of n is misinterpreted is

$$Q=1-(1-P)^n. \tag{29}$$

Clearly, $Q \to 1$, when $n \to \infty$. The above formulas indicate that the outcome depends on both the equipment (instrumentation) performance and the human ability to correctly interpret the obtained information. The formula (29) can be used particularly to assess the effect of the human fatigue on his/her ability to interpret correctly the obtained messages. Let, for instance, $n = 100$ (the navigator receives 100 messages during his/her watch) and $p = 1$: the forecast environmental conditions that the vehicle will encounter will certainly cause an accident and should be avoided. So, the instrumentation did not fail, and the probability p_1 that the navigator obtained this information and that the information has been delivered in a timely fashion is $p_1 = 0.999$. Let the probability that the navigator interprets the information incorrectly is, say, only $p_2 = 0.01 = 1\%$. Then P = 0.001 and Q = 0.0952. Thus, the probability that one message could be misinterpreted is as high as 9.5 %. If the equipment is not performing adequately and the probability p_1 is only, say, $p_1 = 0.95$, then P = 0.05 and Q = 0.9941: one of the messages from the navigation equipment will be most certainly misinterpreted. Thus, we conclude that the performance and the accuracy of the instrumentation are as important as the human factor is.

Problem № 2: The probability that the instrumentation does not fail during the time T of the fulfillment of a certain segment of a mission *is* p_1. The probability that the human «does not fail», i.e., receives and interprets the obtained information correctly (does not make any error) during this time is p_2. It has been established that a certain (non-fatal though) accident has occurred during the time of the fulfillment of this segment of the mission. What is the probability that the accident occurred because of the equipment failure?

Solution: Four hypotheses were possible before the accident actually occurred: H_0 = the equipment did not fail and the human did not make any error; H_1 = the equipment failed, but no human error occurred; H_2 = the equipment did not fail, but the human made an error; H_3 = the equipment failed and the human made an error. The probabilities of these hypotheses are

$$P(H_0) = p_1 p_2;\ P(H_1) = (1-p_1)p_2;\ P(H_2) = p_1(1-p_2);\ P(H_3) = (1-p_1)(1-p_2).$$

The conditional probabilities of the event A «the accident occurred» are

$$P(A/H_0) = 0,\ P(A/H_1) = P(A/H_2) = P(A/H_3) = 1.$$

By applying Bayes' formula

$$P(H_i/A) = \frac{P(H_i)P(A/H_i)}{\sum_{i=1}^{n} P(H_i)P(A/H_i)},\ i = 1,2,\ldots,n,$$

we obtain the following expression for the probability that only the equipment failed

$$P(H_1/A) = \frac{(1-p_1)p_2}{(1-p_1)p_2 + p_1(1-p_2) + (1-p_1)(1-p_2)} = \frac{(1-p_1)p_2}{1-p_1p_2}. \quad (30)$$

Clearly, if the equipment never fails ($p_1 = 1$), then $P = 0$. On the other hand, if the equipment is very unreliable ($p_1 = 0$), then $P = p_2$: the probability that the equipment fails is equal to the probability that the operator did not make an error. If the probabilities p_1 and p_2 are equal ($p_1 = p_2 = p$), then $P = \frac{p}{1+p}$ is the probability that either the equipment failed or the human made an error. For very reliable equipment and a next-to-perfect operator (human) ($p = 1$), $P = 0.5$: the probability that only the equipment failed is 0.5. For very unreliable equipment and very «imperfect» human $(p=0)$ we obtain $P=0$: it is quite likely that both the equipment failed and the human made an error.

Problem № 3. The assessed probability that a certain segment of a mission will be accomplished successfully, provided that the environmental conditions are favorable, is p_1. This probability will not change even in unfavorable environmental conditions, if the navigation equipment is adequate and functions properly. If, however, the equipment (instrumentation) is not perfect, then the probability of safe fulfillment of the given segment of the mission is only $p_2 \lhd p_1$. It has been established that the probability of failure-free functioning of the navigation equipment is p_*. It is known also that in this region of the navigation space unfavorable navigation conditions are observed at the given time of the year in *k%* of the time. What is the probability of the successful accomplishment of the mission in any environmental conditions? What is the probability that the navigator used the equipment, if it is known that the mission has been accomplished successfully?

Solution. The probability of the hypothesis H_1 «the environmental conditions are favorable» is $P(H_1)=1-\frac{k}{100}$. The probability of the hypothesis H_2 «the environmental conditions are unfavorable» is $P(H_2)=\frac{k}{100}$. The conditional probability $P(A/H_1)$ of the event A «the navigation is safe» when the environmental conditions are favorable is $P(A/H_1)=p_1$. The conditional probability $P(A/H_2)$ of the event *A* «the navigation is safe» when the environmental conditions are unfavorable can be determined as

$$P(A/H_2)=p_*p_1+(1-p_*)p_2,$$

so that the sought probability of accident-free navigation on the given segment is

$$P(A)=\left(1-\frac{k}{100}\right)p_1+\frac{k}{100}\left[p_*p_1+(1-p_*)p_2\right]=p_1-\frac{k}{100}(p_1-p_2)(1-p_*).$$

If it is known that the mission has been accomplished successfully despite unfavorable environmental conditions, then

$$P(A/H_2)=\frac{\frac{k}{100}\left[p_*p_1+(1-p_*)p_2\right]}{P(A)}=\frac{\frac{k}{100}\left[p_*p_1+(1-p_*)p_2\right]}{p_1-\frac{k}{100}(p_1-p_2)(1-p_*).}. \quad (31)$$

Let, for instance, $p_1 = 1.0$, $p_2 = 0.95$, $p_* = 0.98$, $k = 80$. Then $P(A) = 0.9992$, $P(A/H_2) = 0.7998$. So, the probability of the successful accomplishment of the mission is 0.9992, and the probability that the navigator used the navigation instrumentation/equipment that enabled him/her to accomplish the mission successfully is 0.7998, otherwise the mission would have failed.

<u>*Problem № 4.*</u> The q_i values for the wave conditions in North Atlantic in the region between 50^0 and 60^0 North Latitude are shown in Table 3 vs. wave heights of 3 % significance (wave heights of 3% significance means that 97 % of the waves are characterized by the heights below the $h_{3\%,m}$ level, and 3 % have the height exceeding this level).

Table 3

Probability of encounter of the environmental conditions of the given level of severity

$h_{3\%,m}$	3	6	9	12	15	18
q_i	0.1500	0.0501	0.0092	0.000876	0.0000437	0.00000115

Two sources of information predict a particular q_i value at the next segment of the route with different probabilities p_1 and p_2. What is the likelihood that the first source is more trustworthy than the second one?

Solution: Let A be the event «the first forecaster is right», $\bar{A}$ be the event «the first forecaster is wrong», B be the event «the second forecaster is right», and $\bar{B}$ be the event «the second forecaster is wrong». So, we have $P(A) = p_1$ and $P(B) = p_2$. Since the two forecasters (sources) made different predictions, the event $A\bar{B} + \bar{A}B$ took place.

The probability of this event is

$$P(A\bar{B} + \bar{A}B) = P(A\bar{B}) + P(\bar{A}B) = P(A)P(\bar{B}) + P(\bar{A})P(B) = p_1(1-p_2) + (1-p_1)p_2.$$

The first forecaster will be more trustworthy if the event $A\bar{B}$ takes place. The probability of this event is

$$P(A\bar{B}) = \frac{p_1(1-p_2)}{p_1(1-p_2) + (1-p_1)p_2} = \frac{1}{1 + \frac{1-p_1}{1-p_2}\frac{p_2}{p_1}}. \qquad (32)$$

The relationship (32) is computed in Table 4. Clearly, $P(A\bar{B}) = 0.5$, if $p_1 = p_2 = p$; $P(A\bar{B}) = 1.0$, if $p_1 = 1$ and $p_2 \neq 1$; $P(A\bar{B}) = 0$, if $p_1 \neq 1$ and

$p_2 = 1$. Other Table 4 data are not counter-intuitive either, but this table quantifies the role of the two mutually exclusive forecasts.

VIII. Most Likely Mental Workload. 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, for instance, [4-25])**.** A pilot's MWL can be measured using subjective ratings or objective measures. The subjective ratings during simulation tests can be in the form of periodic inputs to some kind of data collection device that prompts the pilot to enter a number between 1 and 7 (for example) to estimate the MWL every few minutes. Another possible approach is post–flight paper questionnaires. There are some objective measures of MWL, such as heart rate variability. It is easier to measure the MWL in a flight simulator than in actual flight conditions. In a real airplane, one would probably be restricted to using post-flight subjective (questionnaire) measures, since one would not want to interfere with the pilot's work.

Table 4

Calculated trustworthiness of weather forecast

p_1 / p_2	0.1	0.2	0.4	0.6	0.8	0.9
0.1	0.500	0.692	0.857	0.931	0.973	0.988
0.2	0.308	0.500	0.727	0.857	0.941	0.973
0.4	0.143	0.273	0.500	0.692	0.857	0.931
0.6	0.069	0.143	0.308	0.500	0.727	0.857
0.8	0.027	0.059	0.143	0.273	0.500	0.692
0.9	0.012	0.027	0.069	0.143	0.308	0.500

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 three 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 mental workload, 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 MWL [5]. 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, on the one hand, and the capabilities, motivation and state of the human operator, on the other. 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 psycho-physiological 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.

IX. Most Likely Human Capacity Factor. The HCF includes the person's professional experience; qualifications; capabilities; skills; training; sustainability; ability to concentrate; ability to operate effectively, in a «tireless» fashion, under pressure, and, if needed, for a long period of time; ability to act as a «team-player;» swiftness of reaction, i.e., all the qualities that would enable him/her to cope with high MWL. In order to come up with a suitable FOM for the HCF, one could rank each of the above and other qualities on a scale from one to ten, and calculate the average FOM for each individual.

X. Future Work. The author realizes that the PRM approach, which has proven to be successful in numerous structural reliability problems, including aviation technologies, might not be accepted easily by some psychologists. Some of them may feel that the problem is too complex to lend itself to this type of formalized quantification and might even challenge the approach. With this in mind we would like to suggest several possible next steps (future work) that could be conducted using, when necessary, flight simulators to correlate the distribution (1) 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 navigator's ability to handle stress, or test his/her reaction time, or 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 ***task specific and*** *is* measured in the same units as the MWL is, otherwise the «stress»-»strength» model could not be used. These units could be particularly dimensionless, but should be established for a particular mission or task in advance. ***In addition, HCF has to be multivariate and «dynamic», ta-king into account «static» factors, such as operator's training, experience, native ability, as well as «dynamic» factors, such as fatigue and arousal. For instance, evidence points to elevated levels of air traffic controller operational errors at both low and high-task-demand-levels (i.e., more of a Yerkes-Dodson non-monotonic response), as well as possibly on the downslope after a period of peak arousal [25]. Thus, one might be needing to model the first and even the second time-derivatives of arousal of workload to fully capture all the important effects.*** Other, perhaps, less challenging tasks might include:

1. Testing 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. Carrying out continuous MWL measurements using subjective and/or psycho-physiological measures;
3. Assessing 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. Evaluating the role of weather conditions that might affect the MWL, and might have an effect on the HCF as well;
5. Assessing the role of the «phase of flight» Since descent and landing are characterized by the highest level of MWL, the formulas (1) and (21) should be applied and verified for these conditions. It is the authors' belief 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 comple-xity certainly means more MWL for the pilot to manage;
6. Categorizing the types of errors/outcomes (again, typical and pos-sible errors, not mistakes or blunders: these are beyond any PRM analysis) that might occur. One should determine ahead of time which kind of deviations of normal conditions and what kind of errors/outcomes he/she is interested in. Catastrophic loss of an aircraft usually results from a series of failures − deviations from normal conditions that might lead to a casualty, 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. 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 aerospace industry is concerned, might be applicable, after appropriate modification and

generalization, not only to address (less critical) en-route situations, but landing situations as well.

7. Use the model to compare the performance of different pilots (MCF) for different MWL levels. Of course, even a significant deviation from normal conditions does not necessarily lead to a casualty, and our models were 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 (ALT) and highly accelerated life tests (HALTs) in hardware electronics (see, for instance [22]) with what could be expected from the flight simulation tests.

XI. Conclusions. A DEPDF 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 assess a mission success situation. We have shown how some methods of the classical probability theory could be employed to quantify the role of the human factor in the situation in question. We show that if highly reliable equipment is used, the mission could be still successful, even if the HCF is not very high. The suggested probabilistic risk management (PRM) approach complements the existing system-related and human-psychology-related efforts, and, most importantly, bridges the gap between the three critical areas responsible for the system performance − reliabi-lity engineering, vehicular technologies and human factor. Plenty of additional PRM analyses and human-psychology related effort will be needed, of course, to make the guidelines based on the suggested concept practical for particular applications. These applications might not be even necessarily in the vehicular technology domain, but in many other areas and systems (forensic, medical, etc.), where a human interacts with equipment and instrumentation, and ope-rates in conditions of uncertainty. Although the approach is promising and fruitful, further research, refinement, and validation would be needed, of course, before the model could become practical. The suggested model, after appropriate sensitivity analysis is carried out, might be used 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 deve-loped and installed. The initial numerical data based on the suggested model make physical sense and are in satisfactory (qualitative) agreement with the existing practice. It is important to relate the model expressed by the basic equation (1) to the existing practice, on one hand, and to review the existing practice from the standpoint of this model on the other.

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