THE JOURNAL IS INCLUDED IN THE LIST OF THE LEADING JOURNALS AND EDITIONS OF THE HIGHER ATTESTATION COMMISSION (VAK)

*ISSN 1729-2646*
*e-ISSN 2500-3909*



**THE JOURNAL PROMOTER:**
“Journal “Reliability” Ltd

*It is registered in the Russian Ministry of Press, Broadcasting and Mass Communications. Registration certificate ПИ 77-9782, September, 11, 2001.*

*Official organ of the Russian Academy of Reliability*

**Publisher of the journal**
LLC Journal “Dependability”
**Director**
Dubrovskaya A.Z.
The address: 109029, Moscow, Str. Nizhegorodskaya, 27, Building 1, office 209
Ltd Journal “Dependability”
www.dependability.ru
Printed by JSC “Regional printing house, Printing place” 432049, Ulyanovsk, Pushkarev str., 27. Circulation: 500 copies.
Printing order
Papers are reviewed. Signed print ,
Volume , Format 60x90/8, Paper gloss

Papers are reviewed.
Papers are published in author’s edition. The opinion of members of the editorial board may not coincide with the point of view of authors’ publications. The reprint of materials is granted only with the written permission of the editorial board. Manuscripts are not returned.

**THE JOURNAL IS PUBLISHED WITH THE PARTICIPATION AND SUPPORT OF THE JOINT-STOCK COMPANY «RESEARCH AND DESIGN INSTITUTE OF INFORMATISATION, AUTOMATION AND COMMUNICATION ON RAILWAY TRANSPORT» (JSC «NIIAS») AND LLC PUBLISHING HOUSE «TECHNOLOGY»**

## CONTENTS

## Dear colleagues,

The latest issue (12, no. 1 (44), 2017) of our electronic journal Reliability: Theory and Application is out. The issue is available here and on the first page of our forum. The next issue is scheduled for June 2017. Please send us your papers to allow us time for evaluation. As a reminder, the requirements are as follows: English language, Word of LaTeX format, text size up to 15 pages. Announcements (new conferences, new publications, new area of interest events) are welcome. We also accept brief memoirs of prominent subject matter experts.

Article templates for our journal can be found at:

Template (Word) electronic journal **Reliability: Theory and Application** (Click to download)

Template (LaTeX) electronic journal **Reliability: Theory and Application** (Click to download)

## Dear readers and authors,

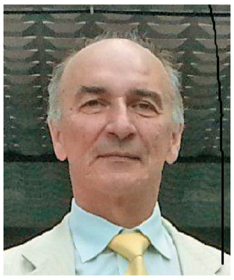
The past year brought significant changes to the life of the Gnedenko Forum and our journal. The President of the Forum has stepped down, while the Editorial Board has been significantly renewed. We hope that together we will be able to not only preserve the spirit and atmosphere of our journal, but also give new momentum to the endeavors started by Igor Ushakov.

In January 2006, the Gnedenko Forum started the publication of the quarterly Reliability: Theory and Application (RT&A). The journal is registered in the US Library of Congress (index 1932-2321). Since the first issue 10 years ago the journal has published 43 numbers and over 400 articles. The papers pass the obligatory editing and are published as PDF files on the journal's website. The journal publishes articles, reviews, memories, information and literature references regarding the theory and application of reliability and quality control, security, survivability, maintenance, risk analysis and management methods. Preference is given to Editorial Board materials that reflect the practical application of such methods. Articles of theoretical nature must identify new aspects of practical application and must not contain excessive formal calculations.

*Original article*
*DOI: 10.21683/1729-2646-2017-17-2-4-10*

# Estimation of the degradation factor of a censored geometrical process

**Alexander V. Antonov,** *Obninsk Institute for Nuclear Power Engineering (IATE MEPhI), Obninsk, Russia*
**Igor F. Moiseev,** *Joint Stock Company All-Russian Research Institute for Nuclear Power Plants Operation (JSC VNIIAES), Moscow, Russia*
**Valeri A. Chepurko,** *Obninsk Institute for Nuclear Power Engineering (IATE MEPhI), Obninsk, Russia*



*Alexander V. Antonov*

*Igor F. Moiseev*

*Valeri A. Chepurko*

**Abstract. Aim.** *The article examines the behaviour of renewable objects that are complex systems and generate temporally unhomogeneous failure flows. The objects' dependability is described with a geometrical processes model. The mathematical model of such processes allows considering both the ageing and renewal of a system. In the first case the failure flow rate increases with time. That corresponds with the period of ageing, when the failure rate progressively grows and the system fails more and more frequently. In the second case, the failures that show high rate at the beginning of operation become rare with time. In technical literature, this stage of operation is called the burn-in period. Normal renewal process is a special case of the geometric process model. In real operation conditions not all operation times end with a failure. Situations arise when as part of preventive maintenance a shortcoming is identified in an observed object, that gets replaced as the result. Or, for a number of reasons, a procedure is required, for which the object is removed from service and also replaced with an identical one. The object that was removed from service is repaired, modernized or simply stored. Another situation of unfinished operation occurs when the observation of an object is interrupted. More precisely, the object continues operating at the time the observation stops. For example, it may be known that at the current time the object is in operation. Both of the described situations classify the operation time as right censored. The task is to estimate the parameters of the mathematical model of geometric process using the known complete and right censored operation times that are presumably governed by the geometric process model. For complete operation times, this task was solved for various distributions [11-16]. As it is known, taking into consideration censored data increases the estimation quality. In this paper the estimation task is solved subject to the use of complete and right censored data. Additionally, the article aims to provide an analytical justification of increased estimation quality in cases when censoring is taken into account, as well as a practical verification of the developed method with real data.* **Methods.** *The maximum likelihood method is used for evaluation of the parameters of the geometrical process model. The likelihood function takes into consideration right censored data. The resulting system of equations is solved by means of the Newton-Raphson method.* **Conclusions.** *The article introduces formulas for evaluation of model parameters according to the maximum likelihood method on the assumption of various distribution laws of the time to first failure. The resulting formulas enable the estimation of the parameters of the geometrical process model involving uncertainty in the form of right censoring. Analytical evidence is produced on increased accuracy of estimation in cases when right censored data is taken into consideration. Parameter estimation was performed based on real operational data of an element of the Bilibino NPP protection control system.*

**Keywords:** *equipment degradation, heterogeneous failure flow, geometric renewal process, process numerator, restorable system, method of maximum likelihood process, right censoring.*

**For citation:** *Antonov AV, Moiseev IF, Chepurko VA. Estimation of the degradation factor of a censored geometric process. Dependability 2017;2: 4-10. DOI: 10.21683/1729-2646-2017-17-2-4-10*

## Introduction

As it is known, in the course of its operation technical equipment goes through several stages. Depending on the stage of operation, equipment dependability indicators change, as do their calculation methods. Until recently, most attention was given to the normal operation period, at which the failure flow parameter (rate) is a nearly constant value. In this case, the equipment operation process is assumed to be homogenous in time, while the dependability indicators are calculated using conventional methods that are, for instance, presented in [1]. Yet calculations of the dependability indicators must take into consideration two other periods: burn-in and heavy wear, when the failure flow parameter first decreases, then increases in time. Generally, there might be other, more complex time dependencies.

In [1-3], there is a short overview of various mathematical models of failure flow nonhomogeneity. Among the primary event flow nonhomogeneity models in current theories are the nonhomogenous Poisson flows, gamma processes, trend-renewal processes, flows based on the normalizing function model, and finally geometric recovery processes.

Geometric processes are described with one of the simplest models of inhomogeneous (in time) recovery processes. The model of these processes appeared quite recently [4-10] and is not yet as popular as the models of conventional recovery processes. That is primarily due to the fact that many theoretical matters related to the properties of such processes, as well as some matters of estimation of parameters of geometric recovery process model under different input data are still poorly studied. Thus, [11-16] set forth and examine some estimation methods (primarily, maximum likelihood method) of the degradation coefficient (denominator) of the geometric recovery process subject to availability of complete statistical information on the failures. In [16], the non-parametric method of confidence interval construction for the geometric process denominator is shown that allows verifying the statistical hypothesis of the presence of one or another geometrical process.

This paper aims to construct an estimation based on the method of maximum likelihood of model parameters in situations when statistical data contains uncertainty in the form of unfinished time between failures. Let us define such operation time as right censored time between failures. Additionally, the paper aims to prove the fact of increasing accuracy of evaluation of the parameters of the examined model if censored data is taken into consideration.

The input data for the required calculations are complete and right censored times between failures of a set of homogeneous elements. For the purpose of this paper, homogeneity is understood as the identity of equipment, identical operating conditions, roughly same age, etc. The operation times have equal dimensions.

## Inhomogeneity of geometric type failure flows

The name of the process is directly associated with the concept of geometric progression. Geometric processes are a generalization of renewal processes. Unlike the normal renewal process that models ideal repair, geometrical process can be used in modelling, for example, of imperfect repair, when the resulting process cycle durations are not distributed evenly. Nevertheless, compared to other inhomogeneous processes the model is quite bare, as the cycle durations are "governed" by the same parameters. Geometric processes (in the context of the dependability theory) were defined in [4-7].

**Definition.** The random value (r.v.) $\xi$ is equal to the r.v. $\eta$ in distribution, if their distribution functions are identical: $F_\xi(x)=F_\eta(x)$. Equality in distribution is denoted as follows.

$$\xi \overset{d}{=} \eta. \quad (1)$$

**Definition.** The sequence of nonnegative (e.g. lifetime) of independent r.v.'s $\{\Delta_k;k=1,2,\dots\}$ forms a geometric process (GP), if equality in distribution is satisfied

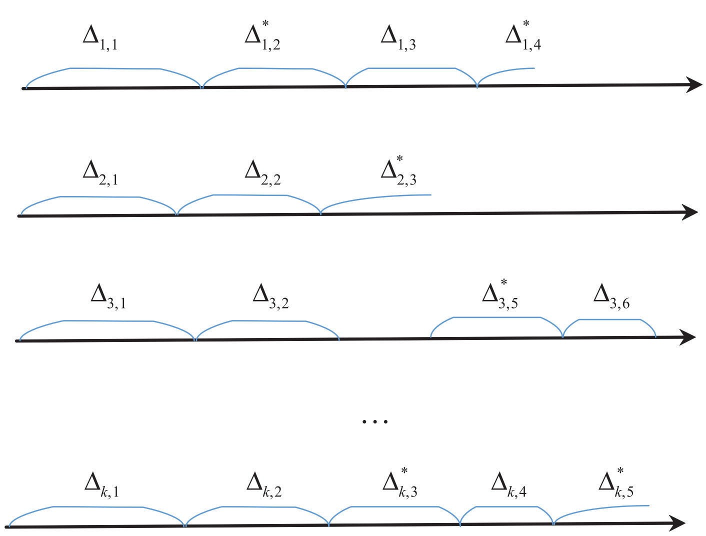


Figure 1. Set of homogenous geometric processes

$$\Delta_{k+1} \overset{d}{=} \gamma\Delta_k, k = 1, 2, ..., \quad (2)$$

where $\gamma > 0$ is the real number constant that, by analogy with the geometric progression, is called the denominator of geometric process. Under values below 1 let us call denominator $\gamma$ the degradation coefficient.

## Input information

Let us assume that observation covers $k$ of single-type immediately recoverable objects each of which has a realization of times between failures (Figure 1). In other words, we can observe $k$ homogenous independent geometric processes. Homogeneity is understood in the way that each process has the same denominator $\gamma$.

Also, let us assume that information is available on incomplete (not ended with failure) times between failures. Thus, in Figure 1, for the first object the complete operation times are the first time, $\Delta_{1,1}$, third time, $\Delta_{1,3}$. The forth time is incomplete, as the geometric process did not end with a failure by the time the observation of this process interrupted. The second time is also incomplete. In real-life conditions that corresponds to a situation when the object under observation was replaced for some reason, e.g. if preventive maintenance identified a serious defect. Obviously, $\Delta^*_{1,2}$ cannot be considered a complete operation time. Thus, the operation time that did not end with failures will be called right censored and we will assume that that could be causes by at least two reasons: interruption of observation or equipment replacement.

Let us denote such incomplete operation times $\Delta^*_{i,j}$ and define the associated geometric process as a right censored geometric process.

Additionally, let us assume that generally the data table may have gaps, e.g. the third object is missing information on the third and forth operation times, while the fifth and subsequent ones are present. This is also true for the incomplete operation times.

Let us transpose the data table, i.e. let us group the information in accordance with the number of operation time. Let the last observed operation time have the number $s$. Let us represent the input information as follows:

$$\left(\left(\Delta_{1,1},...,\Delta_{n_1,1}\right),\left(\Delta^*_{1,1},...,\Delta^*_{m_1,1}\right)\right) \text{ is the realization of the first operation times, } \left(\Delta_1, \Delta^*_1\right); \quad (3)$$

$$\left(\left(\Delta_{1,2},...,\Delta_{n_2,2}\right),\left(\Delta^*_{1,2},...,\Delta^*_{m_2,2}\right)\right) \text{ is the realization of the second operation times, } \left(\Delta_2, \Delta^*_2\right); \quad (4)$$

$$\left(\left(\Delta_{1,s},...,\Delta_{n_s,s}\right),\left(\Delta^*_{1,s},...,\Delta^*_{m_s,s}\right)\right) \text{ is the } s^{\text{th}} \text{ operation times between failures, } \left(\Delta_s, \Delta^*_s\right). \quad (5)$$

In virtue of formula (2) $i$+1 time between failures is related with the first operation time with the following relation in distribution: $\Delta_{i+1} \overset{d}{=} \gamma^i \Delta_1, i = 0,1,...$ Thus, the distribution function $F_{i+1}(x)$, dependability function (PNF) $P_{i+1}(x)$, distribution density $i$+1 of operation time $f_{i+1}(x)$ will be defined based on the respective functional characteristics of the first operation time $F_1(x)$, $P_1(x)$ and $f_1(x)$ similarly to the method set forth in [14]:

$$F_{i+1}(x)=F_1(\gamma^{-i}x),\ P_{i+1}(x)=P_1(\gamma^{-i}x),\ f_{i+1}(x)= \gamma^{-i} f_1(\gamma^{-i}x). \quad (6)$$

Let us now consider the matter of estimation of unknown parameters of the geometric process model on the assumption of the following laws of distribution of the first time between failures:

$$P_1(x)=\exp(-\lambda x^{\beta}), \quad (7)$$

$$P_1(x)=\exp(-\lambda_1 x-\lambda_2 x^2). \quad (8)$$

The dependability function (7) pertains to the Weibull-Gnedenko distribution, (8) describes the distribution with linearly increasing failure rate (see [1]). It is obvious that both (7) and (8) generalize the exponential distribution that is obtained if $\beta = 1$ and $\lambda_1 = \lambda$, $\lambda_2 = 0$ respectively.

Obviously, the distributions (7) and (8) can be generalized by the following distribution:

$$P_1\left(x\right)=\exp\left(-\sum_{l=1}^{p}\lambda_l x^{\beta_l}\right). \quad (9)$$

If $\beta_1=\beta$, $\lambda_1= \lambda$, $\lambda_2=\ldots= \lambda_p=0$ we deduce (7), if $\beta_1=1$, $\beta_2=2$, $\lambda_3=\ldots=\lambda_p=0$ we deduce the distribution (8) and, finally, if $\beta_1=1$, $\lambda_1= \lambda$, $\lambda_2=\ldots= \lambda_p=0$ we deduce the exponential distribution.

Now let us consider the maximum likelihood method as the primary method for estimation of the unknown model parameters.

## Method of maximum likelihood

We will define the model parameter estimators by means of the standard method of maximum likelihood. Let us write the likelihood function by means of (6) and using $\vec{\theta} = \left(\vec{\lambda}, \vec{\beta}\right)$ to denote the vector of (possibly) unknown parameters of the distribution law:

$$L\left(\gamma,\vec{\theta}\right)=\prod_{i=1}^{s}\prod_{j=1}^{n_i} f_i\left(\Delta_{j,i}\right)\prod_{k=1}^{m_i} P_i\left(\Delta^*_{k,i}\right)=$$

$$=\prod_{i=1}^{s}\prod_{j=1}^{n_i}\gamma^{-i+1} f_1\left(\gamma^{-i+1}\Delta_{j,i}\right)\prod_{k=1}^{m_i} P_1\left(\gamma^{-i+1}\Delta^*_{k,i}\right).$$

We can naturally expect that the parameters $\vec{\theta}$ may be partially or completely known.

The log-likelihood function (LLF) will be as follows

$$l\left(\gamma,\vec{\theta}\right)=\sum_{i=1}^{s}\left(\begin{array}{c}\sum_{j=1}^{n_i}\left[\left(-i+1\right)\ln\gamma+\ln f_1\left(\gamma^{-i+1}\Delta_{j,i}\right)\right]+\\+\sum_{k=1}^{m_i}\ln P_1\left(\gamma^{-i+1}\Delta^*_{k,i}\right)\end{array}\right).$$

It is not complicated to deduct a simplified form of the LLF:

$$l\left(\gamma,\vec{\theta}\right)=\sum_{i=1}^{s}\sum_{j=1}^{n_i}\ln f_1\left(\gamma^{-i+1}\Delta_{j,i}\right)+ \\ +\sum_{i=1}^{s}\sum_{k=1}^{m_i}\ln P_1\left(\gamma^{-i+1}\Delta^*_{k,i}\right)-N_1\ln\gamma, \qquad (10)$$

where $N_1=\sum_{i=1}^{s}\left(i-1\right)n_i=n_2+2n_3...+\left(s-1\right)n_s$. (11)

By substituting here the distribution density (9) we deduct formulas for model parameters estimation. After a number of substitutions and simplifications the LLF of the generalized distribution is as follows:

$$l\left(\gamma,\vec{\theta}\right)=\sum_{i=1}^{s}\sum_{j=1}^{n_i}\ln\left(\sum_{l=1}^{p}\lambda_l\beta_l\gamma^{-(i-1)(\beta_l-1)}\Delta_{j,i}^{\beta_l-1}\right)- \\ -\sum_{l=1}^{p}\lambda_l\sum_{i=1}^{s}C_i\left(\beta_l\right)\gamma^{-(i-1)\beta_l}-N_1\ln\gamma. \qquad (12)$$

Let us represent the LLF for specific distributions: Weibull-Gnedenko distribution.

$$l=N_2\cdot\left(\ln\lambda+\ln\beta\right)-\beta N_1\ln\gamma+ \\ +\left(\beta-1\right)C_0-\lambda\sum_{i=1}^{s}C_i\left(\beta\right)\cdot\gamma^{-(i-1)\beta}, \qquad (13)$$

where $N_2=\sum_{i=1}^{s}n_i=n_1+...+n_s$, (14)

Distribution with linearly increasing rate.

$$l=\sum_{i=1}^{s}\sum_{j=1}^{n_i}\ln\left(\lambda_1+2\lambda_2\gamma^{-(i-1)}\Delta_{j,i}\right)- \\ -\sum_{l=1}^{2}\lambda_l\sum_{i=1}^{s}C_i\left(\beta_l\right)\gamma^{-(i-1)\beta_l}-N_1\ln\gamma. \qquad (15)$$

Exponential distribution.

$$l=N_2\ln\lambda-N_1\ln\gamma-\lambda\sum_{i=1}^{s}C_i\left(1\right)\cdot\gamma^{-(i-1)}, \qquad (16)$$

In formulas from (12) to (15) the following designations are introduced:

$$C_0=\sum_{i=1}^{s}\sum_{j=1}^{n_i}\ln\left(\Delta_{j,i}\right),\ C_i\left(\beta\right)=\sum_{j=1}^{n_i}\left(\Delta_{j,i}\right)^{\beta}+\sum_{k=1}^{m_i}\left(\Delta^*_{k,i}\right)^{\beta}. \qquad (17)$$

## Substantiation of censoring consideration

Let us examine the degradation coefficient estimation under LLF (16), as it is the simplest one. If the rate of the exponential law is know, the estimation of parameter γ will be the solution of the equation:

$$\frac{\partial l}{\partial\gamma}=-\frac{N_2}{\gamma}+\lambda\left(\frac{C_2\left(1\right)}{\gamma^2}+\frac{2C_3\left(1\right)}{\gamma^3}+...+\frac{\left(s-1\right)C_s\left(1\right)}{\gamma^s}\right)=0. \qquad (18)$$

Thus, the estimation $\hat{\gamma}$ is the solution of the equation $\varphi\left(\hat{\gamma}\right)=\frac{N_2}{\lambda}$, where

$$\varphi\left(\gamma\right)=\frac{C_2\left(1\right)}{\gamma}+\frac{2C_3\left(1\right)}{\gamma^2}+...+\frac{\left(s-1\right)C_s\left(1\right)}{\gamma^{s-1}}.$$

As $C_i(\beta)\geq 0$, then φ(γ) is a monotonically decreasing function with a range space in the form of half line (0,+∞), and equation (18) has an unambiguous solution. Let us calculate the second LLF derivative:

$$\frac{\partial^2 l}{\partial\gamma^2}=\frac{N_2}{\gamma^2}-\lambda\left(\frac{2C_2\left(1\right)}{\gamma^3}+\frac{6C_3\left(1\right)}{\gamma^4}+...+\frac{\left(s-1\right)sC_s\left(1\right)}{\gamma^{s+1}}\right).$$

The second LLF derivative at the bending point $\hat{\gamma}$ will be defined by the formula:

$$\left.\frac{\partial^2 l}{\partial\gamma^2}\right|_{\gamma=\hat{\gamma}}=-\frac{\lambda}{\hat{\gamma}^2}\left(\frac{C_2\left(1\right)}{\hat{\gamma}}+\frac{4C_3\left(1\right)}{\hat{\gamma}^2}+...+\frac{\left(s-1\right)^2C_s\left(1\right)}{\hat{\gamma}^{s-1}}\right)<0. \qquad (19)$$

The last inequation once again proves that the bending point $\hat{\gamma}$ is the maximum point. Yet the most important deduction out of (19) is that taking into account censored operation times according to (17) increases the $C_i(1)$ coefficients. That increases the "steepness" of the LLF and, consequently, the accuracy of the resulting evaluations.

## Practical application

In order to demonstrate the capabilities of the geometric processes model let us consider an example of its practical application in statistical analysis of failure data of compensated neutron chambers (KNK-56) of the reactor control and protection system (CPS) of the Bilibino NPP. Earlier (e.g. see [17]) a similar analysis established that a number of CPS elements, including KNK-56, generate temporally unhomogeneous failure flows (Figure 2).

In the figure we can note a relatively high failure rate in the 1980s followed by a low failure rate. The fact of inhomogeneity was evidenced by a number of related statistical criteria [17].

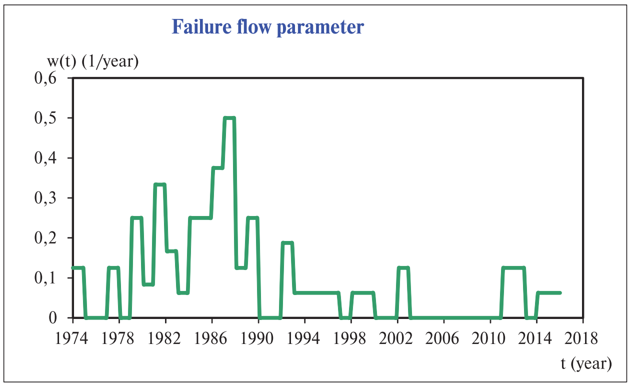



Figure 2. KNK-56 failure flow parameter

It can be expected that this behaviour of the rate will somehow correspond with the geometric process model, whereby with the denominator $\gamma$ >1. This conclusion enabled a preliminary analysis of sufficiently representative failure statistics that became available recently (Table 1).

Table 1 shows selected times between failures of the first five out of 16 (four for each of the 4 BNPP units) KNK-56 elements. With the operation times $\Delta_{j,i}$ is given the «data completeness indicator» $\delta_{j,i}$ that equals 1 if the respective operation time is complete, and 0 if, among other things, it is right censored.

Let us set forth the calculated parameters of models (12) to (15) from Table 2. It must be noted that the calculations using the model with linearly increasing rate (14) matched the results of the exponential law calculations (15), which indicates that the second parameter, the rate $\lambda_2$ under such initial conditions is redundant. Therefore, it was decided to use the generalized model (9) with the number of summands

$p$=2: $P_1(x)=\exp\left(-\lambda_1 x^{\beta_1}-\lambda_2 x^{\beta_2}\right)$.

Judging by the maximum LLF value in Table 1, the most appropriate distribution law model is the generalized model (9) and the Weibull-Gnedenko distribution. Importantly, in each case the geometric process parameter was larger than 1. I.e. the hypothesis regarding this parameter suggested above was presumably correct. A substantiated decision regarding the adequacy of the geometric process model is possible based on either the confidence interval, or the statistical test comparable to [16]. Respective research is to be conducted in the future.

In conclusion, let us take a look at Figures 3 and 4. The former shows the frequency diagram of time between the

**Table 1. Times between failures of KNK-56**

| Element | un. 1 – IK1 | | un. 1 – IK10 | | un. 1 – IK18 | | un. 1 – IK9 | | un. 2 – IK1 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Operation time $i$ | $\Delta_{1,i}$ | $\delta_{1,i}$ | $\Delta_{2,i}$ | $\delta_{2,i}$ | $\Delta_{3,i}$ | $\delta_{3,i}$ | $\Delta_{4,i}$ | $\delta_{4,i}$ | $\Delta_{5,i}$ | $\delta_{5,i}$ |
| 1 | 5.900 | 1 | 0.481 | 1 | 0.381 | 1 | 2.833 | 1 | 1.772 | 0 |
| 2 | 7.022 | 0 | 6.036 | 1 | 7.075 | 0 | 3.556 | 1 | 9.192 | 1 |
| 3 | 0.469 | 1 | 5.700 | 1 | 1.058 | 0 | 0.042 | 1 | 3.931 | 0 |
| 4 | 0.589 | 0 | 0.658 | 1 | 0.003 | 0 | 1.050 | 1 | 0.003 | 1 |
| 5 | 14.494 | 0 | 0.047 | 0 | 0.014 | 1 | 0.622 | 1 | 0.003 | 1 |
| 6 | 13.608 | 0 | 0.608 | 1 | 0.058 | 1 | 12.817 | 0 | 0.450 | 0 |
| 7 | | | 28.183 | 1 | 28.028 | 0 | 15.742 | 0 | 12.289 | 1 |
| 8 | | | 0.369 | 0 | | | | | 3.844 | 0 |
| 9 | | | | | | | | | 6.019 | 1 |
| 10 | | | | | | | | | 3.586 | 0 |

**Table 2. MLM evaluations of model parameters**

| Law | Evaluations | | | | | |
|---|---|---|---|---|---|---|
| Weibull-Gnedenko | $\gamma$ | $\lambda$ | $\beta$ | LLF-$l$ | | |
| | 1.226 | 0.316 | 0.647 | -179.784 | | |
| Linearly increasing rate | $\gamma$ | $\lambda_1$ | $\lambda_2$ | $\beta_1$ | $\beta_2$ | LLF-$l$ |
| | 1.156 | 0.153 | 0 | 1 | 2 | -189.927 |
| Generalized model (9) | $\gamma$ | $\lambda_1$ | $\lambda_2$ | $\beta_1$ | $\beta_2$ | LLF-$l$ |
| | 1.218 | 0.202 | 0.101 | 0.747 | 0.447 | -179.675 |
| Exponential | $\gamma$ | $\lambda$ | LLF-$l$ | | | |
| | 1.156 | 0.153 | -189.927 | | | |

first and the second failure. The latter shows the dependability function (PNF) of the first five KNK-56 operations. We can notice a tendency to progressive improvement of dependability indicators.

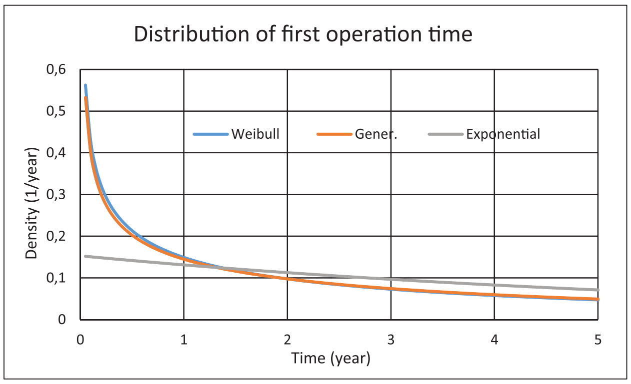



Figure 3. Various distribution models of time between the first and the second failure

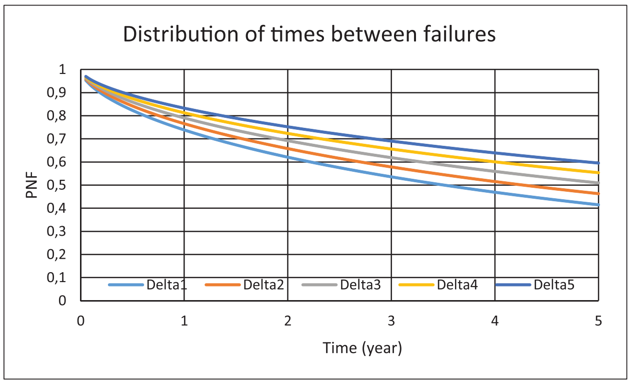



Fig. 4. Dependability functions of the first five times to failure

## Conclusion

The paper presents the geometrical model of renewal processes for the purpose of calculating dependability characteristics of objects that generate temporally unhomogeneous failure flow. The maximum likelihood method is used for evaluation of the model parameters. The paper continues the research of parameter evaluation in geometrical process model. The key feature of the presented research is the capability to take into consideration right censored data. Such uncertainty occurs when non-failed equipment is replaced or in the case of interrupted observation. The authors analytically demonstrate that such provisions improve the accuracy of evaluation. They provide calculations of parameters of various distribution law models based on the operational data of KNK-56 of the Bilibino NPP RCSS.

## References

1. Antonov AV, Nikulin MS, Nikulin AM, Chepurko VA. Teoria nadiozhnosti. Statisticheskie modeli. Ouchebnoie posobie [Dependability theory. Statistical models. A study guide]. Moscow: NITS INFRA-M; 2012 [in Russian]. + Additional Materials <http//www.znanium.com>. ISBN 978-5-16-010264-1

2. Chepurko SV, Chepurko VA. Modeli neodnorodnykh potokov v teorii vosstanovlenia. Monografia [Non-uniform streams models in the renewal theory. A monograph]. Obninsk: IATE; 2012 [in Russian].

3. Finkelstein MS. A scale model of general repair. Microelectronics and Reliability 1993;33:41-46.

4. Saienko NB. Ouchiot nepolnoty vosstanovlenia elementov pri raschiote nadiozhnosti sistem [Accounting for incomplete recovery of elements in systems dependability calculation]. Izvestia vuzov. Priborostroenie 1994;37:11-12 [in Russian].

5. Lam Y. Geometric processes and replacement problem. Acta Mathematicae Applicatae Sinica, English Series 1988;4(4):366–377.

6. Lam Y. A note on the optimal replacement problem. Advances in Applied Probability 1988;20:479–482.

7. Lam Y. Some limit theorems in geometric processes. Acta Mathematicae Applicatae Sinica, English Series 2003;3(19):405–416.

8. Braun WJ, Li W, Zhao YQ. Properties of the geometric and related processes. Naval research logistics 2005;52:607–616.

9. Antonov AV, Chepurko VA. On some characteristics of geometric processes. Journal of Reliability and Statistical Studies 2012 Apr;5(S):1-14.

10. Antonov AV, Chepurko VA. Researching some characteristics of geometric processes. Proceedings of the International Conference on Risk analysis. Limassol (Cyprus); 2011. p. 9-17.

11. Antonov AV, Poliakov AA. One Statistical Age-Dependent Reliability Model in Operating of Nuclear Power Plant Equipment. MMR' 2007. International Conference on Mathematical Methods in Reliability. "Methodology, Practice and Interference". Glasgow (Great Britain); 2007.

12. Antonov AV, Karaulov IN, Chepurko VA. Optimizatsia provedenia profilakticheskikh rabot s ouchiotom diagnostiki i starenia oborudovania [Optimization of routine maintenance subject to degradation and ageing of equipment]. Diagnostika i prognozirovanie sostoyania slozhnykh sistem: sbornik naouchnykh trudov No. 16 kaf. ASU [Diagnostics and forecasting of complex systems condition: Proceeding of the Department of Automated Control Systems no. 16]. Obninsk: IATE;2006:31-37 [in Russian].

13. Antonov AV, Karaulov IN, Chepurko VA. The optimization of carrying out maintenance taking into consideration the degradation and ageing of equipment. Proceedings of the International Conference Degradation, damage, fatigue and accelerated life models in reliability testing. Anger (France); 2006. p. 122-125.

14. Antonov AV, Poliakov AA, Chepurko VA. Otsenka parametrov modeli geometricheskogo protsessa metodom maksimalnogo pravdopodobia [Evaluation of the parameters of geometric process model through the maximum likelihood method]. Dependability 2012;3(38):33-41 [in Russian].

15. Antonov AV, Poliakov AA, Chepurko VA. Model analiza nadiozhnosti obiektov s nepolnym vosstanovleniem [Dependability analysis model for objects with incomplete recovery]. Dependability 2011;3(38):33-41 [in Russian].

16. Chepurko SV, Chepurko VA. Ob odnom metode obnaruzhenia neodnorodnosti potoka otkazov oborudovania AES [On one of the methods of detection of failure flow non-uniformity of NPP equipment]. Izvestia VUZov. Yadernaia energetika 2012;2:65-73 [in Russian].

17. Moiseev IF, Antonov MM et al. Veroyatnostny analiz pokazateley nadiozhnosti i ostatochnogo resursa oborudovania i podsistem SUZ Bilibinskoy AES za period 1974-2010. Tekhnicheski otchiot [Probabilistic analysis of dependability and residual life indicators of subsystems of the Bilibino NPP RCSS based on the failure information for the 1974-2010 period. A technical report]. Moscow: VNIIAES; 2011.

## About the authors

**Alexander V. Antonov**, Professor, Doctor of Engineering, Associate Professor of Cybernetics, Obninsk Institute for Nuclear Power Engineering. 1 Studgorodok, 249020, Russia, Kaluga Oblast, Obninsk, e-mail: chepurko@iate.obninsk.ru

**Igor F. Moiseev**, Project Manager, Candidate of Physics and Mathematics, Joint Stock Company All-Russian Research Institute for Nuclear Power Plants Operation (JSC VNIIAES). 25 Ferganskaya Str., 109507, Russia, Moscow, e-mail: mif898@mail.ru

**Valeri A. Chepurko**, Associate Professor of Automated Control Systems, Candidate of Physics and Mathematics, Obninsk Institute for Nuclear Power Engineering. 1 Studgorodok, 249020, Russia, Kaluga Oblast, Obninsk, e-mail: chepurko@iate.obninsk.ru

**Received on 20.12.2016**

Original article
DOI: 10.21683/1729-2646-2017-17-2-11-16

# Characteristic features of LUT setting codes of Intel FPGAs

**Sergey F. Tyurin,** *Perm National Research Polytechnic University, Perm, Russia*
**Andrey S. Prokhorov,** *Perm National Research Polytechnic University, Perm, Russia*

*Sergey F. Tyurin*

*Andrey S. Prokhorov*

**Abstract.** *State-of-the-art digital circuit design widely uses field programmable gate arrays (FPGAs), in which the functions of logic cells and their connections are set up. That is defined in the configuration file that is loaded in the configuration memory cells (static random access memory) of FPGA from external memory. The logic itself is implemented in the so-called LUTs (Look Up Tables), multiplexors that implement memory cells, are based on transmitting transistors and represents a tree that is activated by a specific variable collection. The setting is multiplexor data, therefore logical (switching) function values for the specific collection are transmitted to the tree output. As it turns out, the associated LUT setting code can be decoded and used for analyzing synthesis results in Quartus II by Altera that has been acquired by Intel. Now Intel also specializes in FPGA production. The article considers an example of the synthesis of a simple combinational finite state machine that implements the so-called majority function (2 out of 3). This function equals 1 if the majority of variables equals 1. Majority function implementation diagram is synthesized in Quartus II that builds a special BDF (Block Diagram/Schematic File) file. The resulting diagram is examined with Map Viewer. In the appropriate diagram, LUT (Logic Cell Comb) setting codes for implementation of the specified function are set forth in the form of four-digit hexacodes. Decoding is shown for setting codes for logic cells of FPGA LUT type that describe the content of the respective truth tables of functions that depend on the input variable machine. The article shows the code changes in the process of diagram optimization by Quartus II with possible modification of the variables sequence order and correspondence with the inputs of a four-input LUT without modifications to the logical function. If Stratix IIGX FPGA is used that has the so-called adaptive logic modules (ALM) with 6 inputs, Quartus II uses 64-bit codes (eight-digit hexacodes). Respective coding is also examined in this paper.*

**Keywords:** *combinational machine, majority function (2 out of 3), logic cells, LUT (Look Up Table), FPGA (Field Programmable Gate Array), Logic Cell Comb, adaptive logic module (ALM).*

**For citation:** *Tyurin SF, Prokhorov AS. Characteristic features of LUT setting codes of Intel FPGAs. Dependability 2017; 2: 11-16. DOI: 10.21683/1729-2640-2017-17-2-11-16*

## 1. Introduction

Field Programmable Gate Arrays (FPGA) are based on random access memory (RAM) units called LUT (Look Up Table) [1-3]. The RAM units contain configuration information in the form of truth tables of the required logical functions.

The QuartusII system by Altera (US) that manufactures the FPGA allows synthesizing finite state machines. The machine is defined not only by a diagram in the form of BDF (Block Diagram/Schematic File), but also in the VHDL, Verilog, AHDL and other hardware description languages, as well as the State Machine File machine graph. QuartusII generates setting codes of logic cells.

Of interest is the decoding of this configuration data (Logic Cell Comb) and their comparison with specified logical functions of the machine. Let us define a simple machine and examine the associated setting codes.

## 2. Resulting truth tables for a four-input LUT

Let us assume that it is required to synthesize the implementation diagram for the three-variable switching function (SF) no. 132. Let us build a truth table (Figure 1).

| Variables | | | BC | f(abc) | |
|---|---|---|---|---|---|
| a | b | c | | | |
| 0 | 0 | 0 | 0 | 0 | $2^0$ |
| 0 | 0 | 1 | 1 | 0 | $2^1$ |
| 0 | 1 | 0 | 2 | 0 | $2^2$ |
| 0 | 1 | 1 | 3 | 1 | $2^3$ |
| 1 | 0 | 0 | 4 | 0 | $2^4$ |
| 1 | 0 | 1 | 5 | 1 | $2^5$ |
| 1 | 1 | 0 | 6 | 1 | $2^6$ |
| 1 | 1 | 1 | 7 | 1 | $2^7$ |

Fig. 1. SF truth table no. $132_{10}$

This SF no. $132_{10}$ is a so-called majority function that in disjunctive normal form (DNF) is as follows:

$$f(abc) = ab \vee bc \vee ac = \overline{\overline{ab \vee bc \vee ac}} = \overline{\overline{ab} \cdot \overline{bc} \cdot \overline{ac}}.$$

Let us manually build the diagram of the form BDF (Block Diagram / Schematic File), Figure 2.

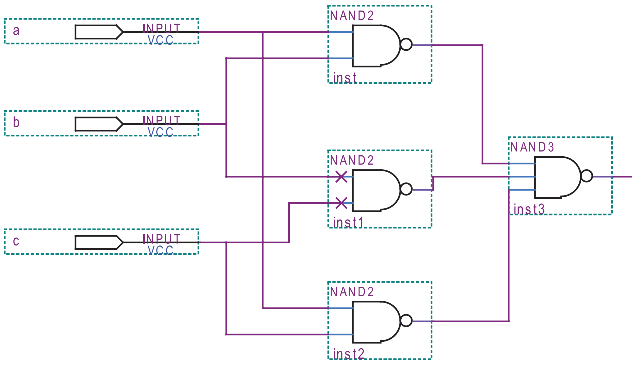



Fig. 2. Basic circuit diagram of the majority function in the form of QuartusII BDF (Block Diagram / Schematic File)

In Figure 2, the diagram inputs are marked as bus "+" of the $V_{cc}$ power supply unit, the inputs are "pulled up" to the voltage, i.e. at the inputs in the initial state there are logical units. By FPGA-compiling the project (e.g. EP2-C5AF256A7) we obtain a report file (Figure 3).

| | |
|---|---|
| Flow Status | In progress - Sat Jan 23 12:05:46 2016 |
| Quartus II Version | 9.0 Build 132 02/25/2009 SJ Web Edition |
| Revision Name | Lab1 |
| Top-level Entity Name | Lab1 |
| Family | Cyclone II |
| Device | EP2C5AF256A7 |
| Timing Models | Final |
| Met timing requirements | N/A |
| Total logic elements | 1 / 4,608 ( < 1 % ) |
| Total combinational functions | 1 / 4,608 ( < 1 % ) |
| Dedicated logic registers | 0 / 4,608 ( 0 % ) |
| Total registers | 0 |
| Total pins | 4 / 158 ( 3 % ) |
| Total virtual pins | 0 |
| Total memory bits | 0 / 119,808 ( 0 % ) |
| Embedded Multiplier 9-bit elements | 0 / 26 ( 0 % ) |
| Total PLLs | 0 / 2 ( 0 % ) |

Fig. 3. Diagram compilation results in the EP2C5A-F256A7 FPGA

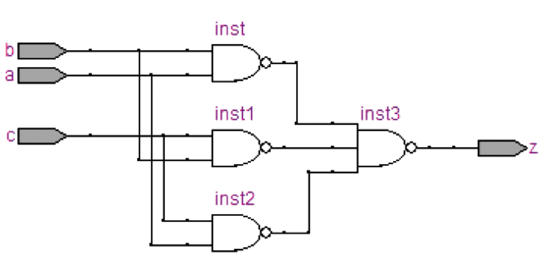



Fig. 4. RTL file

Let us analyze the report produced by Map Viewer. The RTL (register transfer level) diagram is shown in Figure 4.

The RTL diagram is practically identical to BDF and does not contain configuration information, but it is present in the report of the Technology Map Viewer in the hexacode form (Post Mapping, after the allocation of FPGA cells in the "map") (Figure 5).

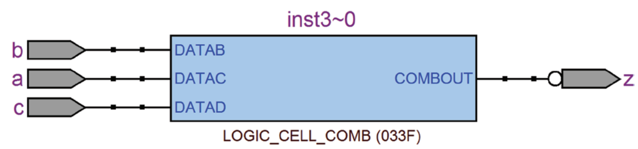



Fig. 5. Technology Map Viewer (Post Mapping)

Thus, QuartusII by Altera has "packed" our diagram into a single FPGA logic cell. Let us decode the 033F setting code of the logic cell LOGIC_CELL_COMB (Figure 6) by comparing the input variables with the 4-input logic cell inputs.

| D | C | B | A | 033F code | f(abc) |
|---|---|---|---|---|---|
| c | a | b | ~ | | |
| 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 0 | 0 | 1 | 1 | 0 |
| 0 | 0 | 1 | 0 | 1 | 0 |
| 0 | 0 | 1 | 1 | 1 | 0 |
| 0 | 1 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 1 | 1 | 0 |
| 0 | 1 | 1 | 0 | 0 | 1 |
| 0 | 1 | 1 | 1 | 0 | 1 |
| 1 | 0 | 0 | 0 | 1 | 0 |
| 1 | 0 | 0 | 1 | 1 | 0 |
| 1 | 0 | 1 | 0 | 0 | 1 |
| 1 | 0 | 1 | 1 | 0 | 1 |
| 1 | 1 | 0 | 0 | 0 | 1 |
| 1 | 1 | 0 | 1 | 0 | 1 |
| 1 | 1 | 1 | 0 | 0 | 1 |
| 1 | 1 | 1 | 1 | 0 | 1 |

Fig. 6. 033F decoding – Post Mapping

As we can see, the coding, as it should, begins with the higher orders of the truth table, where the inputs of the logic cell are in the order D, C, B, A, while the variables are in the order c, a, b. As Figure 5 shows a z output inversion, the 033F code is an inversion of the desired majority function f(abc). As we can see (Figure 5), input A is not used because the function depends on tree variables and QuartusII chose to use only the inputs B, C and D.

Let us now examine Technology Map Viewer (Post Fitting, i.e. after connections optimization), Figure 7.

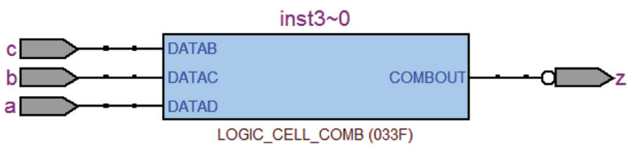



Fig. 7. Technology Map Viewer (Post Fitting)

Figure 7 shows that input connections have changed, which probably is the optimization of connections. Let us decode the code with the new variable connections.

| D | C | B | A | 033F code | f(abc) |
|---|---|---|---|---|---|
| a | b | c | ~ | | |
| 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 0 | 0 | 1 | 1 | 0 |
| 0 | 0 | 1 | 0 | 1 | 0 |
| 0 | 0 | 1 | 1 | 1 | 0 |
| 0 | 1 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 1 | 1 | 0 |
| 0 | 1 | 1 | 0 | 0 | 1 |
| 0 | 1 | 1 | 1 | 0 | 1 |
| 1 | 0 | 0 | 0 | 1 | 0 |
| 1 | 0 | 0 | 1 | 1 | 0 |
| 1 | 0 | 1 | 0 | 0 | 1 |
| 1 | 0 | 1 | 1 | 0 | 1 |
| 1 | 1 | 0 | 0 | 0 | 1 |
| 1 | 1 | 0 | 1 | 0 | 1 |
| 1 | 1 | 1 | 0 | 0 | 1 |
| 1 | 1 | 1 | 1 | 0 | 1 |

Fig. 8. 033F decoding – Post Fitting

The 033F coding does not change, because the majority function does not depend on the variables sequence order. Thus (from top to bottom) 033F is acquired.

## 3. Acquisition of the truth tables for a six-input ALM

Now, let us define a more complex Stratix IIGX FPGA that has the so-called adaptive logic modules (ALM) with not 4, but 6 inputs [4-6]. We obtain a report (Figure 9).

We can see that the report in Figure 9 features adaptive LUTs (ALUTs), their coding is 64-bit, i.e. 16 hexadecimal digits (Figure 10).

As previously, there is an output inversion. Let us decode part by part the setting, code E8E8E8E8E8E8E8E8, that also should be an inversion of the majority function. We will take into consideration the additional inputs F and E (Figure 11).

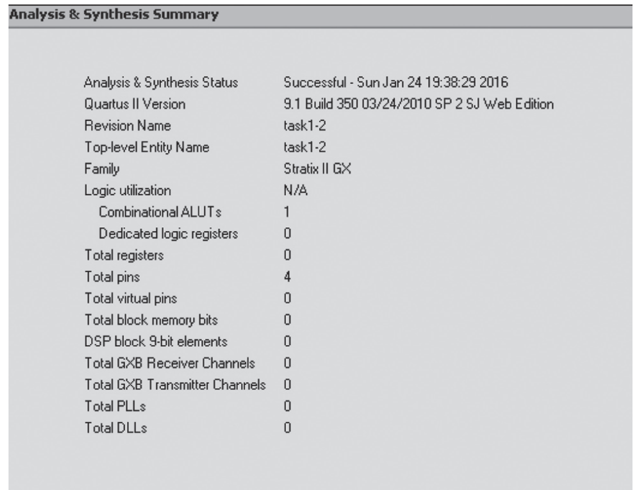



Fig. 9. Stratix IIGX FPGA compilation results


Fig. 10. Technology Map Viewer (Post Mapping) for a Stratix IIGX FPGA diagram

| F | E | D | C | B | A | E8E8 | f(abc) |
|---|---|---|---|---|---|---|---|
| ~ | ~ | ~ | b | c | a | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 |
| 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 |
| 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 |
| 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 |
| 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 |
| 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 |
| 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 |
| 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 |
| 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 |

Fig. 11. Decoding of a part of E8E8 code (Post Mapping), first part of the truth table

However, in this case the majority function is not implemented. An inversion is implemented instead. Why? Let us try the coding from low orders (Figure 12).

Thus, the noncompliance of the ALUT settings with the required function can be explained by the “inverted” coding, i.e. from low orders (from the top of the table in Figure 12). That might be caused by the large size of the truth table.

| F | E | D | C | B | A | E8E8 | f(abc) |
|---|---|---|---|---|---|---|---|
| ~ | ~ | ~ | b | c | a | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 |
| 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
| 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 |
| 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 |
| 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 |
| 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 |
| 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |

Fig. 12. Decoding of a part of E8E8 code from low orders (Post Mapping), first part of the ALUT truth table

The remaining three parts of the truth table are shown in Figures 13 – 15.

| F | E | D | C | B | A | E8E8 | f(abc) |
|---|---|---|---|---|---|---|---|
| ~ | ~ | ~ | b | c | a | | |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 |
| 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 |
| 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |
| 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 |
| 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 |
| 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |
| 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| 0 | 1 | 1 | 1 | 0 | 1 | 0 | 1 |
| 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |

Fig. 13. Decoding of a part of E8E8 code from low orders (Post Mapping), second part of the ALUT truth table

Let us examine the coding of Post Fitting for a Stratix IIGX FPGA diagram (Figure 16).

We can see that now the variables have "shifted" towards the higher orders F and E. Therefore, the code is different. Let us verify the implementation of the specified function (Figure 17).

| F | E | D | C | B | A | NOT f(abc) | f(abc) |
|---|---|---|---|---|---|---|---|
| ~ | ~ | ~ | b | c | a | | |
| 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 |
| 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
| 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 |
| 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 |
| 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 |
| 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 |
| 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |

Fig. 14. Decoding of a part of E8E8 code from low orders (Post Mapping), third part of the ALUT truth table

| F | E | D | C | B | A | NOT f(abc) | f(abc) |
|---|---|---|---|---|---|---|---|
| ~ | ~ | ~ | b | c | a | | |
| 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 |
| 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 |
| 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 |
| 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |
| 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 |
| 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 |
| 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |
| 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 |
| 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |

Fig. 15. Decoding of a part of E8E8 code from low orders (Post Mapping), forth part of the ALUT truth table

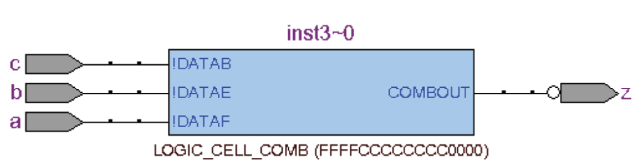



Fig. 16. Technology Map Viewer (Post Fitting) for a Stratix IIGX FPGA diagram

| F | E | D | C | B | A | FFFF code | f(abc) |
|---|---|---|---|---|---|---|---|
| a | b | ~ | ~ | c | ~ | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 |
| 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 |
| 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 |
| 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 |
| 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 |
| 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 |
| 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 |
| 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 |

Fig. 17. Decoding of the first part the ALUT FFFF code from low orders (Post Fitting)

| F | E | D | C | B | A | CCCC code | f(abc) |
|---|---|---|---|---|---|---|---|
| a | b | ~ | ~ | c | ~ | | |
| 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 |
| 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 |
| 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 |
| 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 |
| 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 |
| 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
| 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 |
| 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 |
| 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 |
| 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 |
| 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |

Fig. 18. Decoding of the second part the ALUT CCCC code from low orders (Post Fitting)

## 4. Conclusions

Given the above, the hexacodes, LUT configuration data (LOGIC_CELL_COMB), can be transformed into truth tables of the respective logical functions. The variables sequence order (the "base" of variables) can be arbitrary and changes when the diagram is optimized (when changing from Post Mapping to Post Fitting), yet the function itself remains unchanged.

| F | E | D | C | B | A | CCCC code | f(abc) |
|---|---|---|---|---|---|---|---|
| a | b | ~ | ~ | c | ~ | | |
| 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 |
| 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 |
| 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
| 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 |
| 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 |
| 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 |
| 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 |
| 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 |

Fig. 19. Decoding of the third part the ALUT CCCC code from low orders (Post Fitting)

| F | E | D | C | B | A | 0000 code | f(abc) |
|---|---|---|---|---|---|---|---|
| a | b | ~ | ~ | c | ~ | | |
| 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |
| 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 |
| 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 |
| 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |
| 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 |
| 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 |
| 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 |
| 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 |
| 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 |
| 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |

Fig. 20. Decoding of the forth part the ALUT 0000 code from low orders (Post Fitting)

The coding discrepancy (LOGIC_CELL_COMB) between the Stratix IIGX FPGAs with a 6-variable adaptive logic module (64 bits, 16 hexadecimal digits) and FPGAs with a 4-variable LUT (16 bits, 4 hexadecimal digits) can be explained by the use of "reverse" coding. In this case, LOGIC_CELL_COMB starts with not the higher, but the lower orders of the truth table. The above decoding should complement laboratory classes of the implementation of digital machines in the Quartus system [7].

## References

1. Ugriumov EP. Tsyfrovaya skhemotekhnika: oucheb-noie posobie [Digital circuit design: a study guide]. Saint Petersburg: BHV-Petersburg; 2004 [in Russian].

2. Tsybin S. Programmiruemaia kommutatsia PLIS: vzgliad iznutri [Software switching of FPGA: a look from the inside], <http://www.kit-e.ru/articles/plis/2010_11_56.php> [accessed on 16.12.2014] [in Russian]/

3. An Ultra-Low-Energy, Variation-Tolerant FPGA Architecture Using Component-Specific Mapping [Electronic resource], <http://thesis.library.caltech.edu/7226/> [accessed on 11.11.14].

4. Zolotukha R, Komolov D. Stratix III — novoye semeystvo FPGA firmy Altera [Statix III, a new FPGA family by Altera], <http://kit-e.ru/assets/files/pdf/2006_12_30.pdf> [accessed on 28.11.2015] [in Russian].

5. Ispolzovanye resursov PLIS Stratix III firmy Altera pri proektirivanii mikroprotsessornykh yader [Use of the resources of Stratix III FPGA by Altera in the design of microprocessor cores], <http://www.kit-e.ru/articles/plis/2010_2_39.php> [accessed on 27.11.2015] [in Russian].

6. Logic Array Blocks and Adaptive Logic Modules in Stratix III Devices, <https://www.altera.com.cn/content/dam/altera-www/global/zh_CN/pdfs/literature/hb/stx3/stx3_siii51002.pdf> [accessed on 29.11.2015] [in Russian].

7. Tyurin SF, Gromov OA, Grekov AV. Realizatsia tsifrovykh avtomatov v systeme Quartus firmy Atera: laboratorny praktikum [Implementation of digital machines in the Quartus system by Altera: a laboratory practicum]. Perm: PNRPU Publishing; 2011 [in Russian].

## About the authors

**Sergey F. Tyurin**, Honourable Inventor of the Russian Federation, Doctor of Engineering, Professor of Automation and Remote Control, Perm National Research Polytechnic University. Perm, Russia, e-mail: tyurinsergfeo@yandex.ru

**Andrey S. Prokhorov**, post-graduate, Department of Automation and Remote Control, Perm National Research Polytechnic University. Perm, Russia, e-mail: npoxop007@yandex.ru.

**Received on 06.03.2016**

Original article
DOI: 10.21683/1729-2646-2017-17-2-17-23

# Method of evaluation of the railway track's availability for traffic operations

**Yuri A. Kuvashov,** *JSC NIIAS, Moscow, Russia, e-mail: kya2003@inbox.ru*
**Evgeni O. Novozhilov,** *JSC NIIAS, Moscow, Russia, e-mail: eo.novozhilov@vniias.ru*

*Yuri A. Kuvashov*

*Evgeni O. Novozhilov*

**Abstract. Aim.** *The maintenance of Russia's railway network requires significant expenditures in order to support the dependability of infrastructure facilities operation. When resources are limited, a wrong decision can cause errors in maintenance planning. The activities of track enterprises define normal operation of the railway infrastructure as a system. Rational management of infrastructure facilities requires the availability of objective real-time information on their dependability and functional safety. One of the key indicators that characterizes the dependability of track is the availability coefficient. When evaluating partially available facilities, it must be considered how partial non-fulfilment or reduced quality of its functions impacts the availability. The conventional formula for the technical availability coefficient allows for only two possible facility states: operable and non-operable. Such evaluation of the technical availability coefficient does not, for instance, allow for reduced availability as a result of a speed restriction on a line section, as well as the impact of a failure of a line section on the overall availability of the line. Therefore, this article deals with the method of evaluation of the technical availability coefficient of a line section subject to its partial operability, as well as considers the approach to the standardization of the technical availability coefficient of a line section.* **Methods.** *The evaluation of the technical availability coefficient of a line section subject to its partial operability involved a system analysis of factors that reduce track capacity. Among such factors are speed restrictions and interruption of traffic due to scheduled and non-scheduled maintenance operations. A three-dimensional graphic model of dependency of movement speed from linear coordinates and time is suggested. It was used to deduce the formulas for evaluation of the technical availability coefficient of single and n-track lines. An approach to the standardization of individual components of the technical availability coefficient was considered. Correlations were deduced for calculation of standard value of the technical availability coefficient of single and n-track lines.* **Conclusions.** *Upon an examination of the factors that cause partial operability and non-operability of railway track, the authors offer a method for evaluation of the technical availability coefficient of a railway line subject to the effects of speed restrictions on the capacity and thereby the availability of track. Aspects of standardization of the technical availability coefficient were examined. Formulas were obtained that allow calculating the actual availability coefficient of a railway line subject to partial operability, as well as the standard value of this indicator. The approaches and methods that are considered in this paper aim to improve the objectivity of evaluation of track availability to enable well-founded decision-making in operation.*

**Keywords:** *railway track, technical availability coefficient, traffic speed restriction, standardization of availability coefficient, partial operability.*

**For citation:** *Novozhilov EO, KuvashovYuA. Method of evaluation of the railway track's availability for traffic operations. Dependability 2017;2: 17-23. DOI: 10.21683/1729-2646-2017-17-2-17-23*

## Introduction

The maintenance of Russia's railway network requires significant expenditures in order to support the dependability of infrastructure facilities operation and safety of traffic.

When resources are limited, a wrong decision can cause errors in maintenance planning. On the one hand, those line sections that require maintenance according to existing standards may have a sufficiently high level of dependability, which mean that the cost of maintenance would not be justified. On the other hand, sections affected by dependability problems can be still operated without modernization, overhauls or scheduled maintenance, which in turn causes increased risks of transportation incidents.

Currently, in the railway infrastructure, the cost of fixed assets of the track facilities accounts for over 60 percent of the total cost of JSC RZD fixed assets, while the operating costs of track infrastructure amount to around 35 percent of the total costs [1]. Thus, the activities of the track facilities define normal operation of the railway infrastructure as a system.

Rational management of infrastructure facilities requires the availability of objective real-time information on their dependability and functional safety.

One of the key indicators that characterizes the dependability of track is the availability coefficient, a composite indicator. According to [2], the operational availability coefficient and technical availability coefficient are distinguished.

The problem of evaluation of potentially partially available facilities is that it must be considered how partial nonfulfilment or reduced quality of their functions impacts the availability indicator itself. The conventional formula for the technical availability coefficient allows for only two possible facility states: operable and non-operable. Thus, as per [2] the railway track technical availability coefficient is defined according to the formula:

$$C_{t.a.} = \frac{T_{op}}{T_{op} + T_{schM} + T_r}, \quad (1)$$

where $T_{op}$ is the total time of railway track being operational over the considered operation period;

$T_{schM}$ is the total time of railway track being in scheduled maintenance and repair over the same period of time;

$T_r$ is the total time to railway track recovery over the same period of time.

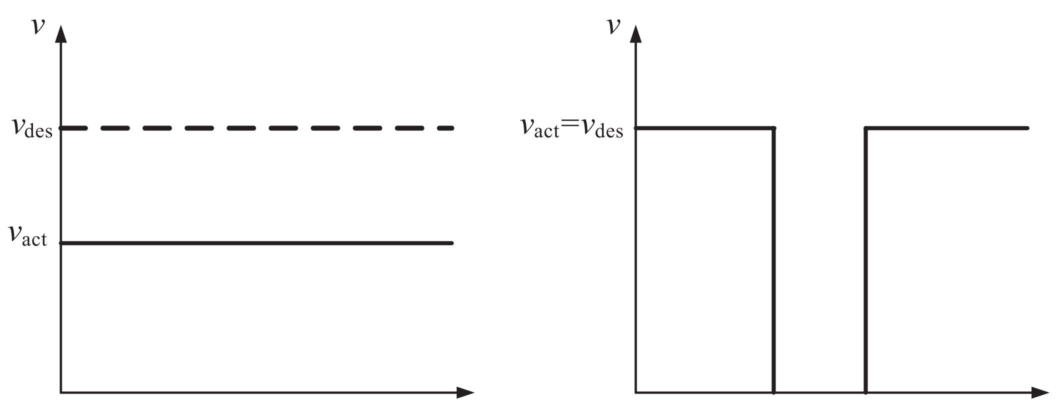
As it follows from formula (1), railway track can be either operable, or under scheduled maintenance and repair, or recovering after failure (the last two states are non-operable). Such evaluation of the technical availability coefficient does not, for instance, allow for reduced availability as a result of a speed restriction at a line section, as well as the impact of a failure of a line section on the overall availability of the line. Given the above, this article deals with the method of evaluation of the technical availability coefficient of a line section subject to its partial operability. Also, it considers the approach to the standardization of the technical availability coefficient of a line section.

## Factors affecting a line section availability

Let us examine a single-track section. The maximum capacity of such section is defined by the design traffic speed and the proportion of time when the track is not under scheduled maintenance and repair.

On the one hand, if a speed restriction is imposed on a track section, the track will only use a part of its capacity, which can be considered a state of partial operability (the reduction of actual speed $v_{act}$ compared to the design speed $v_{des}$ along the whole length $l$ of the section, Figure 1, a). On the other hand, as track is an extended facility, when a part of a section length is non-operable, it can be said that the section as a whole is in the state of partial operability (reduction of speed $v_{act}$ to 0 on a part of section length $l$, Figure 1, b). In practice, the two cases shown in Figure 1 can combine. In addition, within the given time period speed restrictions may occur several times within a track section, each lasting its individual period of time.

Thus, if a speed restriction is in place or a part of the section has failed, as well as in combined scenarios, it can be deemed that the track section is in the state of partial operability and therefore has the availability coefficient



a) b)

Figure 1. Traffic speed restriction within a track section (a) and failure of a part of track section (b)

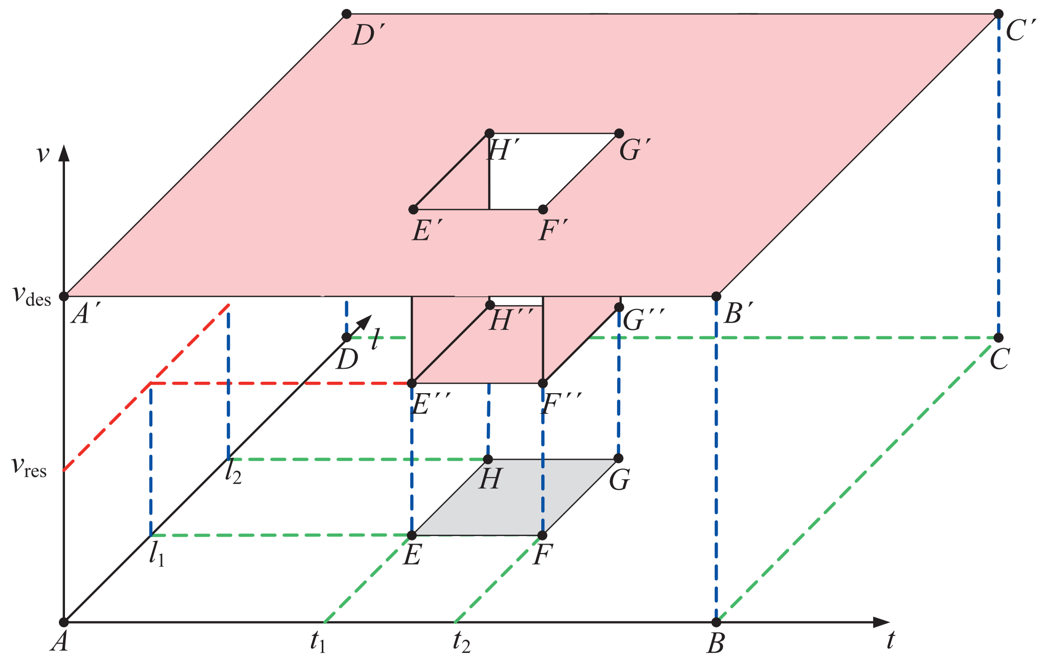



Figure 2. An example of the dependency of traffic speed *v* within the section from the length *l* and the time *t*

of 1. In terms of the technical availability coefficient it should also be noted that a track section is non-operable during scheduled maintenance and repair (planned possessions).

Given the above, it is advisable, when evaluating a track section's availability, to consider the function of speed *v* of the length (linear coordinate) *l* and of the time *t*. An example of such function is shown in Figure 2 in the form of a three-dimensional graph.

In the graph (Figure 2), the traffic speed is per the design value $v_{des}$ except the part of the section from $l_1$ to $l_2$, where within the time period from $t_1$ to $t_2$ the speed restriction $v_{rest}$ is in place. Therefore, within the time period from $t_1$ to $t_2$ the part of section from $l_1$ to $l_2$ is in the state of partial operability (train traffic is ensured, yet at a speed below the nominal value). Consequently, the track section as a whole is in the state of partial operability. As we can see in Figure 2, the case of full availability of the track section corresponds to the parallelepiped *ABCDA′B′C′D′*, while the case of partial availability corresponds to the same parallelepiped minus the volume of the parallelepiped *E′′F′′G′′H′′E′F′G′H′*.

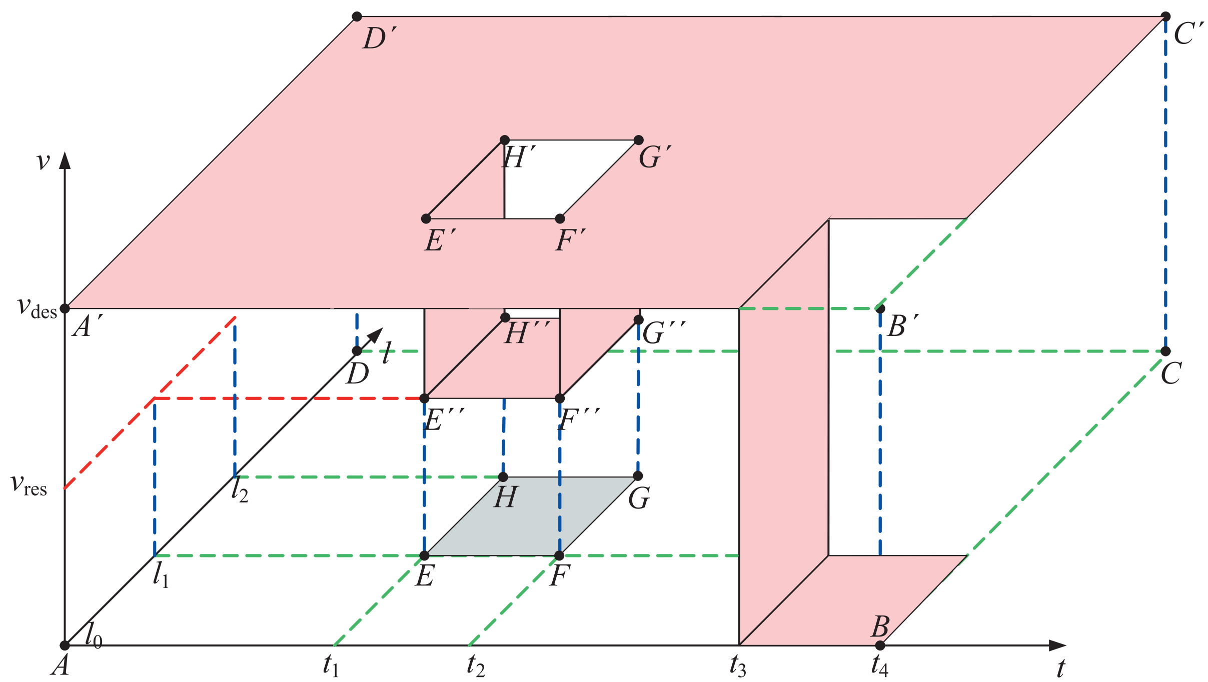



Figure 3. An example of the dependency of traffic speed *v* within the section from the length *l* and the time *t* subject to the maintenance possession

## Evaluation of the technical availability coefficient of a line section

As per Figure 2, let $L = AD$ denote the length of the section, $T_o = AB$ denote the observation period, h, $\Delta l = l_2 - l_1$ denote the part of the track section with a speed restriction in place, km, and $\Delta t = t_2 - t_1$ denote the active period of the traffic speed restriction, h. Then, for the example shown in Figure 2 the track section availability coefficient can be defined by the formula:

$$C_a = \frac{T_o \cdot L \cdot v_{des} - \Delta t \cdot \Delta l \cdot \left(v_{des} - v_{res}\right)}{T_o \cdot L \cdot v_{des}}. \qquad (2)$$

It should be noted that Figure 2 and (2) do not take into consideration planned maintenance and repair.

In order to consider the evaluation of technical availability let us add to Figure 2 the time interval of scheduled maintenance and repair from $t_3$ to $t_4$ on the part of the section from $l_0$ to $l_1$. As the result we obtain Figure 3.

By denoting the duration of the planned possession as $\Delta t' = t_4 - t_3$, h, denoting the length of the part of the section for which the possession is issued as $\Delta l' = l_1 - l_0$, km, and assuming $v_{res} = 0$, we deduce out of (2) the formula for evaluation of the technical availability coefficient:

$$C_{t.a.} = \frac{T_o \cdot L \cdot v_{des} - \Delta t \cdot \Delta l \cdot \left(v_{des} - v_{res}\right) - \Delta t' \cdot \Delta l' \cdot v_{des}}{T_o \cdot L \cdot v_{des}}. \qquad (3)$$

Formulas (2) and (3) describe special cases that explain the approach to the evaluation of the technical availability coefficient of a line section. In general, we can take for the observation interval a random number of speed restrictions and planned possessions. Also, the line section can have one or more tracks.

Let us transform formula (3) in order to take account of a random number of speed restrictions and planned possessions:

$$C_{t.a.} = \frac{T_o \cdot L \cdot v_{des} - \sum_{j=1}^{m} \Delta t_j \cdot \Delta l_j \cdot \left(v_{des} - v_{desj}\right) - v_{des} \cdot \sum_{k=1}^{p} \Delta t'_k \cdot \Delta l'_k}{T_o \cdot L \cdot v_{des}}, \qquad (4)$$

where $m$ is the number of speed restrictions issued for the section over the observation period $T_o$;

$\Delta t_j$ is the effective time period of the $j^{th}$ ($j = 1 \ldots m$) speed restriction, h;

$\Delta l_j$ is the length of the part of track section for which the $j^{th}$ ($j = 1 \ldots m$) speed restriction, km, has been issued;

$\Delta v_{resj}$ is the value of traffic speed according to the $j^{th}$ ($j = 1 \ldots m$) restriction, km/h;

$p$ is the number of planned possessions provided for the section over the observation period $T_o$;

$\Delta t'_k$ is the effective time of the $k^{th}$ ($k = 1 \ldots p$) planned possession, h;

$\Delta l'_k$ is the length of the part of track section for which the $k^{th}$ ($k = 1 \ldots p$) planned possession, km, has been issued.

Assuming that on the $n$-track section ($n = 1, 2, \ldots$) the lengths of all tracks are equal, as are the design speeds, we deduce out of (4) the formula of the technical availability coefficient for the $n$-track section:

$$C_{t.a.} = \frac{n \cdot T_o \cdot L \cdot v_{des} - \sum_{i=1}^{n} \left[ \sum_{j=1}^{m_i} \Delta t_{ij} \cdot \Delta l_{ij} \cdot \left(v_{des} - v_{resij}\right) - v_{des} \cdot \sum_{k=1}^{p_i} \Delta t'_{ik} \cdot \Delta l'_{ik} \right]}{n \cdot T_o \cdot L \cdot v_{des}}, \qquad (5)$$

where $m_i$ is the number of speed restrictions issued for the $i^{th}$ ($i = 1 \ldots n$) track of the section over the observation time $T_o$;

$\Delta t_{ij}$ is the effective time period of the $j^{th}$ ($j = 1 \ldots m_i$) speed restriction for the $i^{th}$ track, h;

$\Delta l_{ij}$ is the length of the part of track section of the $i^{th}$ ($i = 1 \ldots n$) track, for which the $j^{th}$ ($j = 1 \ldots m_i$) speed restriction has been issued, km;

$\Delta v_{resij}$ is the value of traffic speed according to the $j^{th}$ ($j = 1 \ldots m_i$) restriction for the $i^{th}$ track, km/h;

$p_i$ is the number of planned possessions granted for the $i^{th}$ ($i = 1 \ldots n$) track of the section over the observation period $T_o$;

$\Delta t'_k$ is the effective period of the $k^{th}$ ($k = 1 \ldots p_i$) planned possession for the $i^{th}$ track, h;

$\Delta l'_{ik}$ is the length of the part of the section of the $i^{th}$ track, for which the $k^{th}$ ($k = 1 \ldots p_i$) planned possession, km, has been granted.

In order to coordinate the dimension quantities in the numerator and denominator of the formula (5) with the dimensions used in the conventional formula for the availability coefficient [2], i.e. dimensions of time, the numerator and denominator of (5) by the formula $n \cdot L \cdot v_{des}$:

$$C_{t.a.} = \frac{T_o - \frac{1}{n} \sum_{i=1}^{n} \left[ \sum_{j=1}^{m_i} \Delta t_{ij} \cdot \frac{\Delta l_{ij}}{L} \cdot \left(1 - \frac{v_{resij}}{v_{des}}\right) - \sum_{k=1}^{p_i} \Delta t'_{ik} \cdot \frac{\Delta l'_{ik}}{L} \right]}{T_н} =$$

$$= 1 - \frac{\sum_{i=1}^{n} \left[ \sum_{j=1}^{m_i} \Delta t_{ij} \cdot \frac{\Delta l_{ij}}{L} \cdot \left(1 - \frac{v_{resij}}{v_{des}}\right) - \sum_{k=1}^{p_i} \Delta t'_{ik} \cdot \frac{\Delta l'_{ik}}{L} \right]}{n \cdot T_o}. \qquad (6)$$

As a result, we obtain the formula (6) that enables the evaluation of the technical availability coefficient of the $n$-track section subject to planned possessions and states of partial operability (traffic speed restrictions).

Further, let us consider the approach to the standardization of the technical availability coefficient of a line section.

## Standardization of the technical availability coefficient of a line section

The main purpose of dependability indicators standardization is in the selection of substantiated criteria that serve as the foundation for the definition of thresholds for actual values of indicators. The result of comparison of the actual values with the standard ones enables decision-making regarding the further operation of the evaluated facility.

In order to define the standardization criteria, let us consider the components of the availability coefficient of a track section, by replacing in formula (1) $T_o = T_{op} + T_{schM} + T_r + T_{res}$ ($T_{res}$ is the total loss of time due to speed restrictions over the observation period, h; this component was added to the components of formula (1) based on the considerations given above):

$$C_{t.a.} = \frac{T_o - T_{schM} - T_r - T_{res}}{T_o} \quad (7)$$

Thus (see (7), the technical availability coefficient includes the following components:

1) $T_{schM}$, the total time of scheduled maintenance (repair); this component can be standardized based on the known graph of planned possession assignment:

$$T_{schM} = \frac{1}{L}\sum_{k=1}^{p} \Delta l'_{plk} \cdot \Delta t'_{plk}, \quad (8)$$

where $p$ is the number of planned possessions for a track section within the observation period $T_o$;

$\Delta l'_{plk}$ is the length of the part of track section for which the $k^{th}$ ($k = 1\ldots p$) possession is planned, km;

$\Delta t'_{plk}$ is the duration of the planned $k^{th}$ ($k = 1\ldots p$) possession, h;

$L$ is the length of the track section, km;

2) $T_r$ is the total duration of unscheduled repairs at the section over the observation period, h; this component can be standardized based on the statistical evaluation of the mean time to recovery and the track's dependability function of operation time:

$$T_r = t_r \cdot R(X) \cdot L, \quad (9)$$

where $t_r$ is the mean time to recovery of the section after failure, h;

$R(X)$ is the track's dependability function of operation time, 1/km;

$X$ is the operation time of the track section, mil t gross;

$L$ is the length of the track section, km;

3) $T_{res}$ is the total loss of time due to speed restrictions of the observation time, h; this component can be standardized based on the definition of some allowed values of mean traffic speed restriction and mean duration of restriction, as well as the track's reliability function of the operation time (because as the operation time grows, the number of speed restrictions objectively increases):

$$T_{res} = \left(1 - \frac{v_0}{v_{des}}\right) \cdot t_0 \cdot R(X) \cdot L, \quad (10)$$

where $v_0$ is the mean speed restriction value, km/h;

$v_{des}$ is the design traffic speed for the section, km/h;

$t_0$ is the standard (allowed) duration of the restriction (per 1 km), h;

$R(X)$ is the track's dependability function of operation time, 1/km;

$X$ is the operation time of the track section, mil t gross.

$L$ is the length of the track section, km.

Let us consider the track's reliability function of the operation time. The rail is the most vital component of the track superstructure. Therefore, when constructing the most simple model of the track's reliability function it is advisable to use the function of single rail failure depending on the operation time. Such functions per rail types are considered in [3, 4, 5]. In the calculation example, let us use the single rail failure graph [5] that we will describe with a regression equation of the 4th order (Figure 4):

$$R(X) = \min\left\{\begin{pmatrix} 4,809 \cdot 10^{-12} \cdot X^4 + 7,058 \cdot 10^{-9} \cdot \\ \cdot X^3 - 2,738 \cdot 10^{-6} \cdot X^2 + \\ +0,0013 \cdot X + 0,0409 \end{pmatrix}; q\right\}, \quad (11)$$

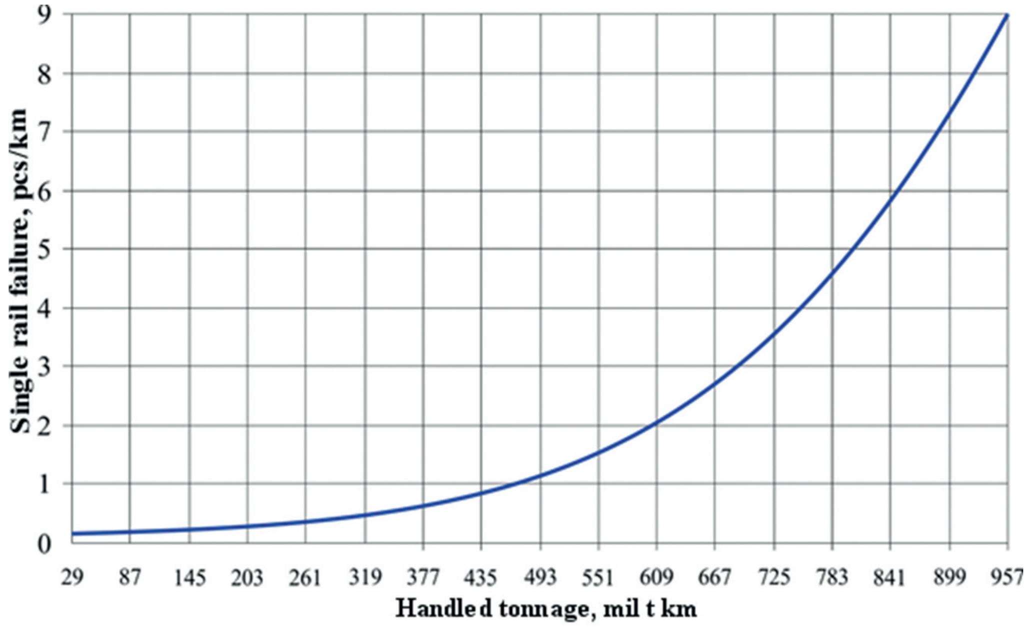



Figure 4. Graph of single rail failure depending on operation time

**Table 1. Results of test calculations of availability of 3rd-class single-track open lines of the Bologoe Track Maintenance Division (PCh-47) of the Oktyabrskaya Infrastructure Directorate based on 2016 data.**

| Open line | Observation period, h | Length, km | Tonnage handled, mil t gross | Length of repaired track and total duration of maintenance possessions | | Number of track circuit failures | | Number of defective rail failures | | Number of track geometry failures | | Number of other failures | | Warnings (ASU VOP-2): 25 km/h speed limit | | Function of single rail failure depending on handled tonnage, 1/km | Technical availability coefficient | Standard technical availability coefficient |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | km | h | pcs | h | pcs | h | pcs | h | pcs | h | pcs | h | | | |
| Sankovo - Podobino | 8760 | 13,3 | 423,84 | 13 | 44,2 | 0 | 0 | 1 | 3 | 0 | 0 | 0 | 0 | 3 | 8,1 | 0,7926 | 0,9939 | 0,9839 |
| Podobino - Bezhetsk | | 11,1 | 388,29 | 10,1 | 104,8 | 1 | 2,4 | 1 | 0,25 | 0 | 0 | 0 | 0 | 2 | 3,2 | 0,6554 | 0,9875 | 0,9804 |
| Bezhetsk - Shishkovo | | 11,9 | 268,45 | 7,9 | 89,5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 2,25 | 0,3541 | 0,9896 | 0,9853 |
| Shishkovo - Viktorovo | | 9,5 | 21,48 | 9,5 | 60,8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 32 | 1026 | 0,0676 | 0,9085 | 0,9924 |
| Viktorovo - Sidorkovo | | 15 | 287,76 | 6 | 24,5 | 1 | 1,6 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 19,45 | 0,3894 | 0,9954 | 0,9911 |
| Sidorkovo - Maksatikha | | 9,3 | 882,48 | 9,3 | 220,7 | 0 | 0 | 4 | 4,3 | 0 | 0 | 0 | 0 | 20 | 289,1 | 6 | 0,9505 | 0,9161 |
| **Total** | | **70,1** | **378,72** | - | - | - | - | - | - | - | - | - | - | - | - | **0,6228** | **0,9752** | **0,9446** |

where $X$ is the operation time of the track section, mil t gross;

$q$ is the standard value of single rail failure for overhaul assignment [6], pcs/km.

Based on the formulas (7) – (11) we obtain the formula for the standard technical availability coefficient of a line section (for a single-track section):

$$C_{t.a.s.}=\frac{T_o-\frac{1}{L}\sum_{k=1}^{p}\left(\Delta l'_{plk}\cdot\Delta t'_{plk}\right)-R(X)\cdot L\left[t_o+\left(1-\frac{v_0}{v_{des}}\right)\cdot t_0\right]}{T_o}, \quad (12)$$

For an $n$-track section under the above assumptions, formula (12) transforms as follows:

$$C_{\text{t.a.s.}}=\frac{\left(\begin{array}{c} T_{\text{o}}-\frac{1}{n\cdot L}\sum_{i=1}^{n}\sum_{k=1}^{p_i}\left(\Delta l'_{\text{pl}ik}\cdot\Delta t'_{\text{pl}ik}\right)- \\ -\left[\sum_{i=1}^{n}R_i(X)\right]\cdot L\left[t_{\text{o}}+\left(1-\frac{v_0}{v_{\text{des}}}\right)\cdot t_0\right]\end{array}\right)}{T_{\text{o}}}, \quad (13)$$

where $p_i$ is the number of planned possessions granted for the $i^{\text{th}}$ ($i = 1\ldots n$) track of the section over the observation time $T_{\text{o}}$;

$\Delta t'_{plik}$ is the effective period of the $k^{\text{th}}$ ($k = 1\ldots p_i$) planned possession for the $i^{\text{th}}$ track, h;

$\Delta l'_{plik}$ is the length of the part of track section of the $i^{\text{th}}$ track, for which the $k^{\text{th}}$ ($k = 1\ldots p_i$) possession is planned, km.

The results of test calculation of the values of actual and standard technical availability coefficient through the means described above are given in Table 1, where the following parameters are used: $t_{\text{r}} = 2$ h; $v_0 = 25$ km/h; $t_0 = 10$ h; $q = 4$.

The authors express their gratitude to the Track and Structures Administration of the Russian Railways Central Directorate for Infrastructure that provided the input data for the test calculations.

The authors express their gratitude to Prof. Igor B. Shubinsky, Doctor of Engineering, for his assistance in the preparation of this article.

## Conclusions

Upon an examination of the factors that cause partial operability and non-operability of railway track, the authors suggest a method for evaluation of the technical availability coefficient of a railway line subject to the effects of speed restrictions on the capacity and thereby the availability of track. Aspects of standardization of the technical availability coefficient were examined. Formulas were obtained that allow calculating the actual availability coefficient of a railway line subject to partial operability, as well as the standard value of this indicator. The approaches and methods that are considered in this paper aim to improve the objectivity of evaluation of track availability to enable well-founded decision-making in operation.

## References

1. Rabchuk SA. Problemnie voprosy razvitiya putevogo kompleksa [Challenges faced by the track facilities]. Evrazia-vesti 2012;VIII:7 [in Russian].

2. GOST R 55443-2013 Railway track. Set of dependability and safety indicators. Approved and came into force by order of the Federal Agency for Technical Regulation and Metrology dated June 25, 2013 no. 186-st. Moscow: Standartinform; 2013 [in Russian].

3. Basilov VV, Chernyshov MA, Editors. Spravochnik inzhenera-putetsa [Handbook for track maintenance engineers]. Moscow: Transport; 1972 [in Russian].

4. Karpushchenko NI, Trukhanov PS. Otsenka i prognozirovanie nadiozhnosti relsov v razlichnykh ekspluatatsionnykh usloviakh [Evaluation and forecasting of dependability of rails under various operating conditions]. Izvestia Transsiba 2016;2(26):118-126 [in Russian].

5. Shchepotkin GK, Velichko DV, Slavikovskaya EA. Tekhniko-ekonomicheskaia otsenka effektivnosti besstykovogo puti v ousloviyakh Sibiri [Feasibility study of the efficiency of jointless track in the Siberian environment]. Novosibirsk: Siberian State University of Railway Engineering Publishing; 2006 [in Russian].

6. Requirements specifications for reconstruction (modernization) and repair of railway track. JSC RZD, Transportation Center; 2013 [in Russian].

## About the authors

**Yuri A. Kuvashov,** Head of Division, JSC NIIAS. Moscow, Russia, tel.: +7 (495) 967 77 05, ext. 558, e-mail: kya2003@inbox.ru

**Evgeni O. Novozhilov,** Candidate of Engineering, Head of Unit, JSC NIIAS. Moscow, Russia, tel.: +7 (495) 967 77 05, ext. 208, e-mail: eo.novozhilov@vniias.ru

**Received on 17.04.2017**

Dependability, vol. 17 no.2 2017 Original article
DOI: 10.21683/1729-2646-2017-17-2-24-30

# Processing of dependability testing data

**Boris I. Filippov**, *Novosibirsk State Technical University, Novosibirsk, Russia*
**Tatiana B. Trush**, *Novosibirsk State Technical University, Novosibirsk, Russia*

*Boris I. Filippov*

*Tatiana B. Trush*

**Abstract. Aim.** *The development of the electronics industry is associated with a fast growth of the products functionality, which in turn causes increasing structural complexity of the radioelectronic systems (RES) with simultaneously more pressing dependability requirements. The currently used methods have several shortcomings, the most important of which is that they allow accurately evaluating reliability indicators only in individual cases. This type of estimation can be used for verification of compliance with specifications, but it does not enable RES dependability analysis after the manufacture of the pilot batch of equipment. That is why the task of identification of dependability indicators of manufactured radioelectronic systems is of relevance.* **Methods.** *The paper examines the a posteriori analysis of RES dependability analysis that is performed after the manufacture of the pilot batch of equipment in order to identify its dependability characteristics. Such tests are necessary because at the design stage the design engineer does not possess complete a priori information that would allow identifying the dependability indicators in advance and with a sufficient accuracy. An important source of dependability information is the system for collection of data on product operational performance. There are two primary types of dependability tests. One of them is the determinative test intended for evaluation of dependability indicators. It is typical for mass-produced products. Another type of test is the control test designed to verify the compliance of a system's dependability indicator with the specifications. This paper is dedicated to the second type of tests.* **Results.** *The question must be answered whether the product (manufactured RES) dependability characteristics comply with the requirements of the manufacturing specifications. This task is solved with the mathematical tools of the statistical theory of hypotheses. Two hypotheses are under consideration: hypothesis $H_0$, mean time to failure $t^*=T_0$ as per the specifications (good product); hypothesis $H_1$, mean time to failure $t^*=T_1<T_0$, alternative (bad product). The hypothesis verification procedure has a disadvantage that consist in the fact that the quality of the solution is identified after the test. Such procedure of hypothesis verification is not optimal. The paper examines the sequential procedure of hypothesis verification (Wald test) that involves decision-making after each failure and interruption of the test if a decision with specified quality is possible. An algorithm is shown for compliance verification of the resulting sample distribution law with the exponential rule or other distribution law over criterion $\chi^2$.* **Conclusions.** *It was shown that the test procedure [n, B, r] ensures the quality of decision identical to that of the procedure [n, V, r] provided the testing time t is identical. Under the sequential procedure, if the number of failures r and testing time are not known from the beginning, a combined method is used (mixed procedure), when additionally the failure threshold limit $r_0$ is defined and the decision rule is complemented with the condition: if $r < r_0$, the sequential procedure is used; if $r = r_0$, normal procedure is used. An algorithm is shown for compliance verification of the resulting sample $w_1(y_i)$ distribution law with the exponential rule or other distribution law over criterion $\chi^2$. The paper may be of interest to radioelectronic systems design engineers.*

**Keywords:***radioelectronic system, test procedures, no-failure operation time, test duration, Neyman-Pearson rule, Wald procedure, $\chi^2$ criterion.*

*For citation:Filippov BI, Trush TB.Processing of dependability testing data. Dependability 2017;2: 24-30. DOI: 10.21683/1729-2646-2017-17-2-24-30*

## Introduction

As it is known, the development of the electronics industry is associated with a fast growth of the products functionality, which in turn causes increasing structural complexity of the radioelectronic systems (RES) with simultaneously more pressing dependability requirements. The currently used methods have several shortcomings, the most important of which is that they allow accurately evaluating reliability indicators only in individual cases [1-4]. This type of estimation can be used for verification of compliance with specifications, but it does not enable RES dependability analysis after the manufacture of the pilot batch of equipment.

Therefore, the task of identification of dependability indicators of manufactured RES is of relevance.

## Problems and solutions

**1. Problems of a posteriori analysis**

A posteriori dependability analysis is performed after the manufacture of the pilot batch of equipment in order to identify its dependability characteristics. For that purpose RES is submitted to statistical testing using one of the procedures described below [5]:

a) procedure [*n*, B, *r*] implies that the test involves *n* RES to *r* failures without replacement of failed systems;

b) procedure [*n*, V, *r*] implies that the test involves *n* RES to *r* failures with replacement of failed systems (renewal);

c) procedure [*n*, B, *T*] implies that the test involves *n* RES within given time *T* (test duration) without replacement of failed systems;

d) procedure [*n*, V, *T*] implies that the test involves *n* RES within given time *T* with replacement of failed systems (renewal);

e) mixed procedures: [*n*, B, *r*/*T*] or [n, V, *r*/*T*] imply specified test duration and number of failures; the tests are stopped when either *r* or *T* reach the specified value; if the test duration to last failure $t_r \leq T$, then the results are processed using procedures a) or b), if $t_r > T$, then the results are processed using procedures c) or d);

f) procedure [*n*, B, *n*], tests are conducted to failure of all *n* RES that participate in the test; this procedure is used rarely, primarily in cases when it is required to identify statistical characteristics of failure sequences of individual RES elements.

Each testing procedure has its advantages and disadvantages, some of which will be shown below.

Test results processing aims to solve one of two tasks:

First task. Identification of dependability indicators of manufactured RES;

Second task. Identification of the degree of compliance of dependability indicators of manufactured RES with the specifications.

The first task is considered in [6].

**2. Identification of the compliance of dependability indicators with the specifications (Second task)**

The verification of RES dependability characteristics compliance with specifications is the second task of dependability testing. The question must be answered whether the product (manufactured RES) dependability characteristics comply with the requirements of the manufacturing specifications. This task is solved with the mathematical tools of the statistical theory of hypotheses [5].

**Definition of goals of the research**

1. As the result of tests as per procedure [*n*, V, *r*] with replacement of (renewal) of failed systems the sample of failure time points ($t_1$, …, $t_r$) was obtained that was used for identification of the sample of times between failures ($y_1$, …, $y_r$).

2. Two hypotheses are under consideration:

- hypothesis $H_0$: mean time to failure $t^*=T_0$ as per the specifications (good product);

- hypothesis $H_1$: $t^*=T_1<T_0$, alternative (bad product).

3. As it is known, the distribution density of times between failures matches the exponential rule (otherwise, the experimental data is verified for compliance with the adopted theoretical model).

4. The decision regarding the correctness of a hypothesis is taken based on the Neyman-Pearson rule, for which under a specified probability of errors of first kind the probability value of the errors of second kind is the lowest.

Based in the test results, the question must be answered as to which of the hypotheses is correct.

**Description of the method to solve the research task**

1. The sample is a point in an*r*-dimensional space *Y*, Figure 1.

Before starting the tests, the sample space must be divided into two spaces in accordance with the adopted decision rule.

$$\text{if}\,(y_1,\dots,y_r)\in y_r^{(H_0)} \xrightarrow{\gamma_0} H_0,$$

$$\text{if}\,(y_1,\dots,y_r)\in y_r^{(H_1)} \xrightarrow{\gamma_1} H_1, \quad (1)$$

where$\gamma_0$ is the decision in favour of the hypothesis $H_0$, while $\gamma_1$ is that in favour of the hypothesis $H_1$.

Wrong decision are also possible:

- error of first kind: $\gamma_0/H_1$, buyer's risk,

- error of second kind: $\gamma_1/H_0$, manufacturer's risk.

Accordingly, the correct decisions are as follows: $\gamma_0/H_0$ and $\gamma_1/H_1$.

2. According to the Neyman-Pearson rule:

- buyer's risk $\alpha=P\{\gamma_0/H_1\}$ (probability of error of first kind is specified by the buyer);

- manufacturer's risk $\beta= P\{\gamma_1/H_0\}$ (probability of error of second kind is minimized by the manufacturer).

Decision quality indicator: $(1-\beta) = P\{\gamma_1/H_1\}$, probability of correct decision that the product is bad.

3. Let us calculate the likelihood ratio

$$L(y_1, y_2, \ldots, y_r) = \frac{w_r(y_1, \ldots, y_r / H_0)}{w_r(y_1, \ldots, y_r / H_1)}.$$

That enables the transformation of the decision rule in the $r$-dimensional space (1) into the decision rule in the one-dimensional space, when the likelihood ratio is compared to a certain threshold

decision $\gamma_0$: $H_0$, if $L(y_1, \ldots, y_r) \geq C$,

decision $\gamma_1$: $H_1$, if $L(y_1, \ldots, y_r) \leq C$.

4. Let us identify the threshold $C$ for the Neyman-Pearson rule.

Threshold $C$ is identified through the specified value α as follows.

$$\alpha = P\{\gamma_0 / H_1\} = P\{L(y_1, \ldots, y_r) \geq C / H_1\} \qquad (2)$$

Let us rewrite the rule (2) as

$$\ln L(y_1, \ldots, y_r) \geq \ln C \text{, then the decision is } \gamma_0, \text{ otherwise } \gamma_1. \qquad (3)$$

Then

$$\ln L(y_1, \ldots, y_r) \geq \ln \prod_{i=1}^{r} \frac{w_1(y_i/H_0)}{w_1(y_i/H_1)} = \sum_{i=1}^{r} \ln\left(\frac{w_1(y_i/H_0)}{w_1(y_i/H_1)}\right),$$

if $y_i$ are independent, then

$$w_r(y_1, \ldots, y_r / H_0) = \prod_{i=1}^{r} w_1(y_i / H_0)$$

Provided failed systems are replaced (procedure [$n$, V, $r$])

$$w_1(y_i / H_0) = \frac{n}{T_0} e^{-\frac{n}{T_0} y_i},$$

where $\lambda_0 = \dfrac{1}{T_0}$ is the allowed failure rate of good products,

$$w_1(y_i / H_1) = \frac{n}{T_1} e^{-\frac{n}{T_1} y_i},$$

where $\lambda_1 = \dfrac{1}{T_1} > \lambda_0$ is the failure rate of the products that do not comply with the specifications.

Then

$$\frac{w_1(y_i/H_0)}{w_1(y_i/H_1)} = \frac{T_1}{T_0} e^{-ny_i\left(\frac{1}{T_0} - \frac{1}{T_1}\right)}$$

and the likelihood ratio becomes as follows

$$\ln L(y_1, \ldots, y_r) = \sum_{i=1}^{r} \left\{ n \frac{T_1}{T_0} - ny_i \left( \frac{1}{T_0} - \frac{1}{T_1} \right) \right\} =$$

$$= r \ln \frac{T_1}{T_0} + n \left[ \frac{1}{T_1} - \frac{1}{T_0} \right] \sum_{i=1}^{r} y_i = r \ln \frac{T_1}{T_0} + \left( \frac{1}{T_1} - \frac{1}{T_0} \right) t_\Sigma. \qquad (4)$$

The decision rule (3) subject to (4) becomes as follows

$t_\Sigma \geq K$, then the decision is $\gamma_0$, otherwise $\gamma_1$,

where the threshold
$$K = f(C) = \frac{C - r \ln \frac{T_1}{T_0}}{\frac{1}{T_1} - \frac{1}{T_0}}. \qquad (5)$$

5. Threshold $K$ can be identified with the help of the $\chi^2$ distribution tables. For that purpose let us rewrite (2) as follows

$$P\{t_\Sigma \geq K / H_1\} = \alpha \qquad (6)$$

and transform the variable $t_\Sigma$ in such a way that the new variable had normalized distribution by $\chi^2$.

It is known, that $t_\Sigma = n \sum_{i=1}^{r} y_i$ is the sum of the exponentially distributed random values $y_i$. Therefore, $t\Sigma$ has an unnormalized distribution by $\chi^2$. In order to normalize it, is in [6], a new variable $\tau = \left( \dfrac{2t_\Sigma}{t^*} \right)$ must be introduced.

Then, provided that the hypothesis $H_1$ corresponds with the mean time to failure $t^* = T_1$, the probability (6) is as follows

$$P\left\{ \frac{2t_\Sigma}{t^*} \geq \frac{2K}{T_1} \right\} = \alpha \text{ or } P\left\{ \tau \geq \frac{2K}{T_1} \right\} = \alpha,$$

where τ has a $\chi^2(2r)$ distribution with $2r$ degrees of freedom.

In this distribution (Figure 2) $\dfrac{2K}{T_1} = \chi^2_\alpha(2r)$, which corresponds with the α% distribution point $\chi^2(2r)$.

Therefore, the threshold (5) equals to

$$K = \frac{T_1}{2} [\chi^2_\alpha(2r)]. \qquad (7)$$

6. For the threshold of the decision (7), let us find the manufacturer's risk β, of which the value for the Neyman-Pearson rule will be minimal.

According to the Neyman-Pearson rule and equation (6)

$$\beta = P\{\gamma_1 / H_0\} \text{ или } \beta = P\left\{ t_\Sigma < K / H_0 \right\}. \qquad (8)$$

Let us proceed to the normalized distribution by $\chi^2(2r)$

$$\beta = P\left\{\frac{2t_\Sigma}{T_0} < \frac{2K}{T_0}\right\}, \text{ or } \beta = P\left\{\tau < \frac{2K}{T_0}\right\},$$

where $\frac{2K}{T_0} = \chi^2_{(1-\beta)}(2r)$, which corresponds with the $(1-\beta)$% distribution point $\chi^2(2r)$, Figure 2.

Given that $T_0$ and $K$ are known, we can identify $(1-\beta)$, the decision quality indicator.

It should be noted that

$$\chi^2_{(1-\beta)}(2r) = \frac{T_1}{T_0}\chi^2_\alpha(2r),$$

$$\frac{\chi^2_{(1-\beta)}(2r)}{\chi^2_\alpha(2r)} = \frac{T_1}{T_0}, \qquad (9)$$

i.e., $\alpha$% and $(1-\beta)$% points of $\chi^2(2r)$ distribution differ as many times as much the mean time to failure $T_1$ obtained as the result of the tests is worse than the specified $T_0$.

Thus, we need to know four parameters: $\frac{T_1}{T_0}, \alpha, \beta, r$ (or $T_1$, $T_0$, $r$, $\alpha$). Normally, tree out of these parameters are specified at the beginning of the tests, while the fourth one is identified.

In conclusion it should be noted that if the test procedure [$n$, B, $r$] is used the decision quality will be identical as under the procedure [$n$, V, $r$], if the same total testing time $t_\Sigma$ is ensured.

## Application interpretation and demonstration of final research results

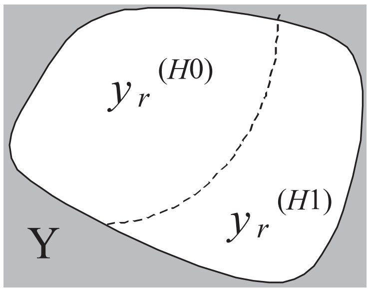



Figure 1. Sample space $Y$

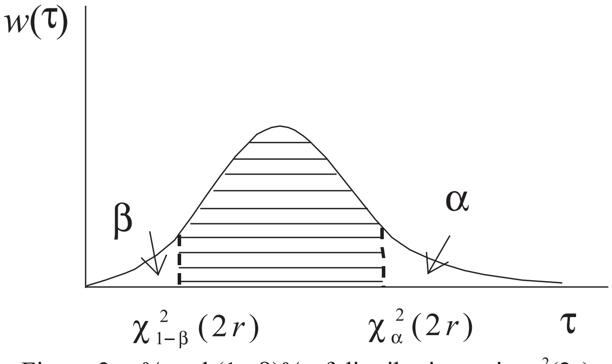



Figure 2. $\alpha$% and $(1-\beta)$% of distribution point $\chi^2(2r)$

Example. Verification of hypothesis of mean time of no-failure

Table 1 shows a sample of the no-failure times obtained as the result of radiotechnical systems dependability testing using plan [1, V, 50], i.e. one RES ($n = 1$) is examined with replacement of failed systems (renewal), where the number of failures is ($r = 50$). Let us consider that renewal after failure happens so quickly that the time of renewal can be ignored.

**Table 1. Sample of no-failure times for RES testing per plan [1, V, 50]**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $i$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $y_i$, h | 118 | 1.5 | 85 | 45 | 169 | 243 | 145 | 49 | 39 | 138 |
| $i$ | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| $y_i$, h | 17 | 267 | 107 | 115 | 331 | 17 | 70 | 20.5 | 5 | 102 |
| $i$ | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| $y_i$, h | 117 | 115 | 112 | 65 | 306 | 93 | 50 | 96 | 71 | 280 |
| $i$ | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 |
| $y_i$, h | 7 | 9.5 | 53 | 4 | 28 | 257 | 364 | 123 | 159 | 116 |
| $i$ | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 |
| $y_i$, h | 52 | 18.5 | 2 | 34 | 35 | 14 | 48 | 1 | 2.5 | 43 |

Let the value of mean time of no-failure be specified as $T_0 = 100$ h. Using the test data, the hypothesis if $T_{mn} = 100$ h must be verified. Let us set the manufacturer's risk as $\alpha = 0.05$. The Neyman-Pearson optimal verification procedure for the above hypothesis, where the number of failures is 50 ($r = 50$), consists in comparing the total system operation time over the testing time with the threshold:

$$K = \frac{T_0}{2}\chi^2_{1-\alpha}(2r) = 50\chi^2_{0,95}(100) = 3896,5 \text{ h}.$$

Using the data from Table 1 let us find the total system operation time during the tests:

$$t_\Sigma = \sum_{i=1}^{50} y_i = 4759,5 \text{ h}.$$

As the total operation time $t_\Sigma = 4759,5$ h, i.e. above the threshold $K = 3896,6$ h, the decision should be taken of the compliance with the specifications. Assuming $T_1 = 75$ h, the buyer's risk $\beta$ can be identified. According to (8.1)

$$\chi^2_{(1-\beta)}(100) = \frac{75 \cdot \chi^2_{0,05}(100)}{100} = 93,265.$$

In the table of percentage points distribution we find:
$1-\beta = 0,67$,
out of which we calculate the buyer's risk $\beta = 0,33$.

## Estimation and hypothesis verification under a small number of failures

Let us show the potential reduction of the quality of estimation of the mean time of no-failure and hypothesis verification regarding this dependability indicator, if the system dependability tests stopped after the 10th failure. Out of the Table 1 we find that the total operation time by the time of the 10th failure is $t_\Sigma = \sum_{i=1}^{10} y_i = 1032,5$ h. The testing time is reduced by $\frac{4759,5}{1032,5} \approx 4,6$ times compared with the testing to the 50th failure. In this case, the maximum likelihood estimation of the mean time of no-failure equals to

$$T_{mn} = \frac{1032,5}{10} = 103,25\ h.$$

From the tables of percentage points of $\chi^2$ distribution we find for the confidence coefficient γ = 0,96.

For tests to the 50th failure under the confidence coefficient γ = 0,96 we deduce

$$\chi^2_{0,5-0,48}(100) = 131,\ \ \chi^2_{0,5+0,48}(100) = 73.$$

The lower confidence contour equals to

$$\frac{2t_\Sigma}{\chi^2_{0,02}(100)} = \frac{9519}{131} \approx 73 \text{ h.}$$

The upper confidence contour equals to

$$\frac{2t_\Sigma}{\chi^2_{0,98}(100)} = \frac{9519}{73} \approx 130 \text{ h.}$$

Thus, the confidence interval for the mean time of no-failure is defined by the equality

$$73 \le T_{mn} \le 130 \text{ h.}$$

The length of the confidence interval is 57 h.

From the tables of percentage points of $\chi^2$ distribution we find for the confidence coefficient γ = 0,96

$$\chi^2_{0,5-0,48}(20) = 35,02,\ \ \chi^2_{0,5+0,48}(20) = 9,24.$$

The lower confidence contour equals to

$$\frac{2t_\Sigma}{\chi^2_{0,02}(20)} = \frac{9519}{35,02} \approx 272 \text{ h.}$$

The upper confidence contour equals to

$$\frac{2t_\Sigma}{\chi^2_{0,98}(20)} = \frac{9519}{9,24} \approx 1030 \text{ h.}$$

Thus, the confidence interval for the mean time of no-failure is defined by the equality

$$272 \le T_{mn} \le 1030 \text{ h.}$$

The length of the confidence interval is 758 h, i.e. almost 14 times longer compared to the tests to the 50th failure under the same confidence coefficient.

Let us now consider the verification of the hypothesis of $T_{mn}$ = 100 h for the sample $r$ = 10. In this case under α = 0,05 the threshold value equals to

$$K = \frac{T_0}{2}\chi^2_{1-\alpha}(2r) = 50\chi^2_{0,95}(20) = 50 \cdot 10,85 = 542,5 \text{ h.}$$

As $t_\Sigma = \sum_{i=1}^{10} y_i = 1032,5$ h, i.e. above the threshold $K$ = 542,5 h, the hypothesis is accepted (product complies with the specifications). Assuming $T_1$ = 75 h, we find the buyer's risk:

$$\chi^2_{(\beta)}(20) = \frac{100}{75} \cdot 10,85 = 14,5,\ \ \beta = 0,8.$$

Thus, the value of the buyer's risk is absolutely acceptable.

Let us increase the manufacturer's risk to α = 0,3. In this case the threshold value will be equal to

$$K = \frac{T_0}{2}\chi^2_{1-\alpha}(2r) = 50\chi^2_{0,7}(20) = 50 \cdot 16,27 = 813,5 \text{ h.}$$

The decision of the correctness of the hypothesis is still in force. We find the buyer's risk

$$\chi^2_{(\beta)}(20) = \frac{100}{75} \cdot 16,27 = 21,7,\ \ \beta = 0,35.$$

We confirm that under sample size $r$ = 10 the probabilistic characteristics of the made decision cannot satisfy neither the buyer, nor the manufacturer and therefore the tests must continue.

## 3. Sequential hypothesis verification procedure

The hypothesis verification procedure considered in section 2 has a disadvantage that consists in the fact that the quality of the solution is identified after the tests (we test first, then we evaluate the result quality). Such procedure of hypothesis verification is not optimal and therefore inefficient.

At the same time there is a sequential procedure of hypothesis verification (Wald test) that involves attempts of decision-making after each failure and interruption of the test if a decision with specified quality is possible. α, β are specified, and using the sequential procedure the statistic $y_1, y_2, \ldots, y_r$ is attempted to be found, that minimizes the average number of failures: $m\{r/H_0\}$ or $m\{r/H_1\}$ required for decision-making.

An accurate solution is difficult to find. In practice, an approximative decision rule is used, when the likelihood ratio is compared to two thresholds:

if $t_\Sigma \le K_1$, the solution is $\gamma_1{:}H_1$ (product does not comply with the specifications);

if $K_0 < t_\Sigma < K_1$, the solution is $\gamma_k$ (tests continue); (10)

if $t_\Sigma \ge K_0$, the decision is $\gamma_0{:}H_0$ (product complies with the specifications).

The shortcoming of the sequential procedure is that the number of failures $r$ and test duration are not known in advance. For that reason a combined method (mixed procedure) is sometimes used, when additionally the failure threshold limit $r_0$ is defined and the decision rule (10) is complemented with the condition:

if $r<r_0$, the sequential procedure is used;

if $r=r_0$, normal procedure is used, e.g. the one considered in section 2.

## 4. Estimation of distribution law

As mentioned above, before identifying the dependability characteristics based on test results we must verify the compliance of the distribution law of the resulting sample $w_1(y_i)$ with the exponential distribution law (e.g. $w_1(y_i) = n\lambda e^{-n\lambda y_i}$ or another). That can be done using criterion $\chi^2$.

**Verification algorithm**

1. Test procedure selection.
2. Testing, obtaining of sample $(t_1, t_2, \ldots t_y)$, $(y_1, y_2, \ldots y_i)$.
3. Test duration is divided into $k$ equal intervals.
4. Identification of the number a failures in each interval $m_i$.
5. Point estimation $\hat{\lambda} = \frac{r-1}{t_\Sigma}$. (11)

Let us assume that the distribution law $y_i$ is exponential.

We calculate the theoretical probability of the number of failures in each interval.

$$P_i = 1 - e^{-n\hat{\lambda}\frac{t_\Sigma}{k}} \tag{12}$$

and estimation of the probability of failures in each interval.

$$\hat{P}_i = \frac{m_i}{r}. \tag{13}$$

Calculation results are tabulated.

We deduce

$$\chi^2 = \sum_{i=1}^{k} \frac{\left(\hat{P}_i - P_i\right)^2}{P_i} \le \chi^2_\alpha\left(k-1-\theta\right), \tag{14}$$

where $\chi^2_\alpha(k-1-\theta)$ is the allowable deviation, $\alpha<<1$, $\theta$ is the number of the evaluated parameters of the distribution law.

If the inequation (14) is true, the resultant experimental results do not contradict the expected theoretical distribution law.

**Example**

Table 2 shows a sample of the no-failure times obtained as the result of radiotechnical systems dependability testing using plan [1, V, 112], i.e. one RES ($n$ = 1) is examined with replacement of failed systems (renewal), where the number of failures is ($r$ = 112). Let us assume that renewal after failure happens so quickly that the time of renewal can be ignored.

Using the data from Table 2 let us find the total system operation time during the tests:

$$t_\Sigma = \sum_{i=1}^{112} y_i = 11363 \text{ h}.$$

Let all the test be divided into $k$ equal intervals ($k$ = 8).

Let us find the point estimate using the formula (11):

$$\hat{\lambda} = \frac{r-1}{t_\Sigma} = \frac{112-1}{11363} = 0{,}0098 \text{ 1/h}.$$

Let us calculate the theoretical probability of the number of failures in each interval using the formula (12) and the evaluation of failure probability using the formula (13) and tabulate the results (Table 3).

The values of the theoretical probability $P_i$ are equal or close to 1, because the value of the right part of the formula (12) tends to 0; e.g., if $k$ = 1: $e^{-n\hat{\lambda}\frac{t_\Sigma}{k}} = 4{,}35\cdot10^{-49} \to 0$.

**Table 2. Sample of no-failure times for RES testing per plan [1, V, 112]**

| $i$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $y_i$, h | 120 | 1.5 | 82 | 45 | 169 | 243 | 145 | 49 | 39 | 138 | 11 | 267 | 108 | 121 | 331 | 17 |
| $i$ | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 |
| $y_i$, h | 70 | 20.5 | 5 | 102 | 117 | 115 | 112 | 65 | 306 | 93 | 50 | 96 | 71 | 280 | 7 | 9.5 |
| $i$ | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 |
| $y_i$, h | 53 | 4 | 28 | 255 | 366 | 123 | 159 | 116 | 52 | 18.5 | 2 | 34 | 35 | 14 | 48 | 1 |
| $i$ | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 |
| $y_i$, h | 2.5 | 43 | 249 | 99 | 104 | 103 | 122 | 32 | 337 | 18 | 19 | 205 | 60 | 8.5 | 154 | 388 |
| $i$ | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 | 80 |
| $y_i$, h | 10 | 4.5 | 9 | 74 | 24 | 177 | 44.5 | 10.5 | 292 | 150 | 21 | 126 | 189 | 16 | 38 | 92 |
| $i$ | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 |
| $y_i$, h | 57 | 31 | 7 | 97 | 108 | 111 | 113 | 70 | 298 | 98 | 69 | 100 | 75 | 275 | 11 | 9 |
| $i$ | 97 | 98 | 99 | 100 | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 108 | 109 | 110 | 111 | 112 |
| $y_i$, h | 7 | 49 | 260 | 88 | 101 | 105 | 117 | 28 | 327 | 15 | 19 | 211 | 67 | 4.5 | 143 | 357 |

**Table 3. Results of dependability calculation**

| Time Interval | $m_i$(number of failures within the interval) | $\hat{P}_i$ (evaluation of failure probability) | $P_i$ (theoretical probability) |
|---|---|---|---|
| 1 | 37 | 0.3304 | 1 |
| 2 | 10 | 0.0893 | 1 |
| 3 | 15 | 0.1339 | 1 |
| 4 | 7 | 0.0625 | 1 |
| 5 | 2 | 0.0179 | 1 |
| 6 | 4 | 0.0357 | 0.999999991 |
| 7 | 3 | 0.0268 | 0.999999877 |
| 8 | 2 | 0.0179 | 0.999999099 |

Then, using the formula (14) let us deduce

$$\chi^2 = 6.71,$$

and with the table of percentage points of $\chi^2$ distribution we will find for $k-1-\theta=k-1-1=6$ degrees of freedom and $\alpha = 0.05$ significance level the threshold value

$$\chi^2_{0,05}(6) = 12,592.$$

Thus,

$$\chi^2 \le \chi^2_{0,05},$$

therefore, according to the goodness-of-fit test $\chi^2$ the exponentiality hypothesis does not contradict the system dependability test results.

## Conclusions

1. The test procedure [$n$, B, $r$] ensures the quality of decision identical to that of the procedure [$n$, V, $r$] provided the testing time $t_\Sigma$ is identical.

2. Under the sequential procedure, if the number of failures $r$ and testing time are not known from the beginning, a combined method is used (mixed procedure), when additionally the failure threshold limit $r_0$ is defined and the decision rule is complemented with the condition:

- if $r<r_0$, the sequential procedure is used;
- if $r=r_0$, normal procedure is used, e.g. the one considered in section 2.

3. An algorithm is shown for compliance verification of the resulting sample $w_1(y_i)$ distribution law with the exponential rule or other distribution law over criterion $\chi^2$.

4. The paper may be of interest to radioelectronic systems design engineers.

## References

1. Zhadnov VV, Polessky SN. Proektnaya otsenkanadiozhnostiradiotekhnicheskikhsystem.Nadiozhnost i kachestvo: tr. Mezhdunar. simpoz.: v 2 t. T. 1 / pod red.Yurkova NK[Engineering estimate of dependability of radiotechnical systems. Dependability and quality: proceedings of international symposium: in 2 vol. Volume 1.Yurkov NK, editor]. Penza: Penza State University Publishing; 2006 [in Russian].

2. Zhadnov VV, Sarafanov AV.Oupravleniekachestvompriproektirovanii teplonagruzhennykh radioelektronnykh sredstv [Quality management in the design of thermally loaded radiolectronics facilities]. Moscow: Solon-Press; 2004 [in Russian].

3. Artiukhova MA, Zhadnov VV, Polessky SN. Metod ouchiota vliania sistemy menedzhmenta nadiozhnosti predpriyatia pri raschiotnoy otsenke pokazatley nadiozhnosti elektronnikh sredstv [Method for accounting of the impact of enterprise dependability management system in estimation of dependability indicators of electronic facilities]. Radioelekpronika, informatika, ouparvlinnia 2013;2:48–53 [in Russian].

4. Filippov BI.Apriornyanaliznadiozhnostiradiotekhnicheskikh sistem bez vosstanovlenia [A priori dependability analysis of radiotechnical facilities without recovery]. IzvestiaVolgGTU, seria Elektronika, izmeritelnaya tekhnika, radiotekhnika i sviaz 2015;11(176):97-103 [in Russian].

5. Levin BR. Teoria nadiozhnosty radiotekhnicheskikh sistem [Dependability theory of radiotechnical systems]. Moscow: Sovietskoye Radio; 1978 [in Russian].

6. Filippov BI. Aposteriorny analiz nadiozhnosti radiotekhnicheskikh sistem [A posteriori dependability analysis of radiotechnical facilities]. Vestnik AGTU, seria Oupravlenie, vychislitelnaya tekhnika i informatika 2015;4:81-91 [in Russian].

## About the authors

**Boris I. Filippov,** Candidate of Engineering, Assistant Professor, Senior Lecturer in Information Protection, Novosibirsk State Technical University. 17Uritskogo Str., app. 13, 630099 Novosibirsk, Russia, phone: +79232256721, e-mail: Fillippov-boris@rambler.ru

**Tatiana B. Trush,** student, Information Protection Department, Novosibirsk State Technical University.192/5 B. Bogatkova Str., app. 183, 630017 Novosibirsk, Russia, phone: +79538075706, e-mail: Tanuza95@mail.ru

**Received on 20.12.2016**

Original article
DOI: 10.21683/1729-2646-2017-17-2-31-35

# Fundamental electrical noises and nondestructive testing of electronic devices

**Boris I. Yakubovich,** *Saint Petersburg Institute of Nuclear Physics, National Research Center Kurchatov Institute, Russia, Gatchina*

*Борис И. Якубович*

**Abstract. Aim.** *The research of potential wide applications of electrical noises in nondestructive testing of electronic devices and theoretic justification of their use for such purposes. To that effect, fundamental electrical noises are examined and the types of those that in principle can be used for nondestructive testing are analyzed.* **Methods.** *The article contains theoretical research finding regarding fluctuation processes behind several types of electrical noise and degradation processes in electronic devices. The connection between the spectral properties of the fluctuations with the characteristics of the degradation processes in electronic devices is analyzed. On this basis, conclusions are made regarding the opportunities of using electrical noises for non-destructive testing of electronic devices. Electrical fluctuation phenomena caused by capture and emission of charge carriers by traps created by structural defects in the solid body structure. The processes of capture and emission of charge carriers by traps are a fundamental cause of the following fundamental types of electrical noise: excess, generation-recombination and burst. Various types of noise significantly differ in terms of the parameters and statistical properties of fluctuation processes. That is the reason for the analysis of electrical fluctuations caused by traps in order to provide a sufficiently general description of such fluctuation phenomena. The work resulted in a rigorous description of the electrical fluctuations caused by traps. A general expression for the fluctuation spectrum was calculated. In special cases, from it we can pass to the spectrums of excess, generation-recombination and bursts noises. The findings regarding the electric fluctuations causes by traps can be used for identification of spectral properties of fluctuations in solid materials and solid-state electronic devices. A rigorous quantitative analysis was made of the degradation processes that occur in solid-state electronic devices in order to establish associations between the spectral characteristics of noises caused by capture and emission of charge carriers by structural defects with the degree of materials defectiveness in order to be able to better exploit the noises in the evaluation of the quality and dependability of electronic devices. It was established that the noise spectral density is associated with the degree and rate of the structure's degradation. Thus, noises in electronic devices contain information on the degree and rate of degradation. The following practical conclusions were made. The noise spectral density is associated with the number of defects in the device at the baseline, as well as the rate of defect formation and, consequently, the ageing rate of the electronic device. Therefore, noise contains information on the quality of the manufactured device and its characteristics change rate. Accordingly, the noise spectrum can be used in evaluation of an electronic device's deficiencies, both those occurring during the manufacturing process, and those that manifest themselves in operation.* **Conclusions.** *The paper substantiates the potential wide applications of electrical noises in non-destructive testing of electronic devices, shows the feasibility of using fundamental types of electrical noises for the above purposes. The rigorous substantiation of the use of electrical noises for nondestructive testing of electronic devices, feasibility of evaluation of the devices' defects caused by various factors, use of common frequently prevailing types of noise, high sensitivity of fluctuation spectroscopy highlight the efficiency of electrical noise in nondestructive testing of electronic devices.*

**Keywords:** *noise, fluctuations, nondestructive testing, dependability, solid bodies, semiconductors, electronic devices.*

**For citation:** *Yakubovich BI, Fundamental electrical noises and nondestructive testing of electronic devices. Dependability 2017;2: 31-35. DOI: 10.21683/1729-2646-2017-17-2-31-35*

## Introduction

Electrical noises can be used in nondestructive testing of electronic devices. That is suggested by many experimental findings. A correlation between the noise characteristics and duration of no-failure operation has been found. Such correlation has been identified in many electronic devices manufactured with the use of various types of solid materials. An overview of the research in that area is given in [1, 2]. The presence of such correlation is attributed to the fact that the origins of a number of noise processes are due to the structural defects of solid materials [2-5]. An increased concentration of defects in a device's structural materials can indicate its potential undependability. There are also reasons to believe that low-frequency electrical noise may be due to degradation processes occurring in electronic devices [6-8]. The potential for using electrical noises for evaluation of defects in solid materials in devices and characterize degradation-related changes in electronic devices makes the noise spectroscopy a sufficiently universal method of nondestructive testing of electronics. The high sensitivity of fluctuation spectroscopy indicates the efficiency of such method.

Given the above, a wider application of noise spectroscopy in nondestructive testing of electronic devices and more rigorous substantiation of the applicability of electrical noises for those purposes are advisable. To that effect, let us examine the fundamental electrical noises, as those can be observed in a wide range of various objects, and analyze those types that in principle can be used in nondestructive testing. Among those are the low-frequency excess, generation-recombination and bursts noises. Low-frequency excess noise is a noise of which the spectral density changes according to the law $S(f)=1/f^{\alpha}$, where $\alpha$ is close to 1. The most significant theoretical model that explains this type of noise associates its origins with the capture and emission of charge carriers by traps created by structural defects in the solid body structure [3, 5]. The generation-recombination noise is caused by generation-recombination processes in semiconductors that in most cases go through centers of generation-recombination formed by structural defects [5, 9, 10]. The burst noise has the form of a random staircase signal and the most convincing explanation of its origins makes reference to the processes of capture and emission of charge carriers by traps under low frequencies of this process [5, 11]. Further, let us analyze the excess, generation-recombination and burst noises, provide a rigorous quantitative description of the underlying fluctuation processes and clarify the connections between the noise spectrums and the degradation processes in electronic devices for the purpose of exploring the potential for using fundamental electrical noises of those types in nondestructive testing of electronic devices.

## Electrical noises

Electrical fluctuation phenomena caused by capture and emission of charge carriers by traps created by structural defects in the solid body structure. The processes of capture and emission of charge carriers by traps is the primary cause of excess, generation-recombination and burst noises. The nature of the noise caused by traps is largely defined by the type of the traps, their concentration, statistical properties of the processes of capture and emission of carriers by traps. The difference primarily in those indicators causes the different types of electrical noise that have the same source, i.e. the stochastic processes of capture and emission of charge carriers by traps. In the given situation, the fluctuations that are due to the total cause of capture and emission of carriers by traps under different additional conditions cause different types of electrical noise. In this context it appears to be advisable to analyze in a fairly general manner the electric fluctuations caused by capture and emission of charge carriers by traps formed by structural defects. Let us analyze the fluctuations with no restrictions on the relations between the parameters of the fluctuation process under the generally defined distributions of times between consecutive events of the fluctuation process. As in electronics semiconductor materials prevail, let us consider electrical fluctuations in semiconductors.

We are examining electrical fluctuations in semiconductors caused by capture and emission of charge carriers by traps formed by structural defects. Transition of free carriers into bound state in traps causes conductivity fluctuations and, consequently, electrical noise in semiconductors. Let us calculate the spectrum of fluctuations in the number of free carriers in a semiconductor caused by traps. Let us analyze the fluctuations generally. The concentrations of free carriers and traps are in random relations. The probability of change of the number of free carriers in a semiconductor is statistically related with the numbers of free carriers, captured carriers and empty traps at the current moment in time. As the number of free carriers in the absence of captures and the number of traps in the sample are fixed, at any moment in time the number of free carriers completely defines the number of captured carriers and empty traps. Let us analyze the fluctuation process, for which the probability of change of the number of free carriers is statistically related with the number of free carriers at the current moment in time and the statistical relation is defined in general. The fluctuations under consideration that are caused by a stochastic process of change of the number $N$ of free carriers have the form of a random sequence of rectangular pulses, of which the amplitude $\delta N$ is defined by formula $\delta N=N-\langle N\rangle$, while the duration of the next pulse equals to the period of time between consecutive events of change of the number of free carriers in the sample (caused by capture and emission of carriers by traps). Under the above statistical relations of the considered fluctuation process the duration of the pulse is statistically related with its amplitude, while the amplitude of the pulse is statistically related with the amplitude of the previous pulse. Let us calculate the spectrum of fluctuations in the number of free carriers in a semiconductor, assuming the fluctuation process is stationary. To that effect, let us calculate the above described random sequence of pulses. The fluctuation of the number of free carriers in a semiconductor can be written as follows:

$$\delta N=\sum_{j=1}^{n}\delta N_j x\left(t-\theta_1-...-\theta_{j-1},\theta_j\right),\qquad(1)$$

where $n$ is the number of pulses in the sequence with the duration $T$, $x(t)$ is the function that describes the pulse form, $\delta Nj$ is the amplitude, $\theta_j$ is the pulse duration. The Fourier transformation is as follows

$$F(f)=\int_{-\infty}^{\infty}\sum_{j=1}^{n}\delta N_j x\left(t-\theta_1-...-\theta_{j-1},\theta_j\right)e^{-2\pi ift}dt=$$

$$=\sum_{j=1}^{n}\delta N_j x\left(t-\theta_1-...-\theta_{j-1},\theta_j\right),\qquad(2)$$

Where

$$F_0\left(f,\theta_j\right)=\int_{-\infty}^{\infty}x\left(t,\theta_j\right)e^{-2\pi ift}dt.\qquad(3)$$

Consequently,

$$\left|F\left(f\right)\right|^2=\sum_{j=1}^{n}\delta N_j^2\left|F_0\left(f,\theta_j\right)\right|^2+$$

$$+2\,\mathrm{Re}\sum_{j=1}^{n-1}\sum_{i=1}^{n-j}\delta N_j^2\delta N_{j+i}e^{2\pi if\left(\theta_j+...+\theta_{j+i-1}\right)}\cdot F_0\left(f,\theta_j\right)F_0^*\left(f,\theta_{j+i}\right).\qquad(4)$$

Let us calculate the assembly average $\left\langle\left|F\left(f\right)\right|^2\right\rangle$ by using the independence of a number of parameters in the considered sequence of pulses

$$\left\langle\left|F\left(f\right)\right|^2\right\rangle=\sum_{j=1}^{n}\left\langle\delta N_j^2\left|F_0\left(f,\theta_j\right)\right|^2\right\rangle+$$

$$+2\,\mathrm{Re}\sum_{j=1}^{n-1}\left\langle\delta N_j\delta N_{j+1}e^{2\pi if\theta_j}\cdot F_0\left(f,\theta_j\right)F_0^*\left(f,\theta_{j+1}\right)\right\rangle+$$

$$+2\,\mathrm{Re}\sum_{j=1}^{n-2}\sum_{i=2}^{n-j}\left\langle\delta N_j e^{2\pi if\theta_j}F_0\left(f,\theta_j\right)\right\rangle\cdot$$

$$\cdot\left\langle\delta N_{j+i}F_0^*\left(f,\theta_{j+i}\right)\right\rangle\left\langle e^{2\pi if\theta_{j+1}}\right\rangle...\left\langle e^{2\pi if\theta_{j+i-1}}\right\rangle.\qquad(5)$$

Let us calculate the spectrum density of fluctuation of the number of free carriers

$$S_N\left(f\right)=\lim_{T\to\infty}\frac{\left\langle\left|F\left(f\right)\right|^2\right\rangle}{T}.\qquad(6)$$

Given the stationary nature of the stochastic process under consideration we deduce the spectral density of fluctuations as follows:

$$S_N\left(f\right)=v\left\{\left\langle\delta N^2\left|F_0\left(f,\theta\right)\right|^2\right\rangle+\right.$$

$$+2\,\mathrm{Re}\left\langle\delta N_j\delta N_{j+1}e^{2\pi if\theta}F_0\left(f,\theta_j\right)F_0^*\left(f,\theta_{j+1}\right)\right\rangle+$$

$$\left.+2\,\mathrm{Re}\left\langle\delta NF_0^*\left(f,\theta\right)\right\rangle\left\langle\delta Ne^{2\pi if\theta}F_0\left(f,\theta\right)\right\rangle\frac{\left\langle e^{2\pi if\theta}\right\rangle}{1-\left\langle e^{2\pi if\theta}\right\rangle}\right\},\qquad(7)$$

where $v=\lim_{T\to\infty}n/T$ is the average number of captures and emissions of carriers by traps per time unit. Obviously, $v=1/\langle\theta\rangle$. Let us calculate the Fourier transformation of a single pulse, given that the pulse is rectangular

$$F_0\left(f,\theta\right)=\int_0^{\theta}x\left(t\right)e^{-2\pi ift}dt=\frac{e^{-\pi if\theta}\sin\pi f\theta}{\pi f}.\qquad(8)$$

As a result, the spectrum of fluctuations of the number of free carriers in semiconductors under random proportion of concentrations of traps and free carriers is as follows

$$S_N\left(f\right)=\frac{1}{\pi^2f^2\langle\theta\rangle}\left\{\left\langle\delta N^2\sin^2\pi f\theta\right\rangle+\right.$$

$$+2\,\mathrm{Re}\left\langle\delta N_j\delta N_{j+1}e^{\pi if\left(\theta_j+\theta_{j+1}\right)}\sin\pi f\theta_j\sin\pi f\theta_{j+1}\right\rangle+$$

$$\left.+2\,\mathrm{Re}\left\langle\delta Ne^{\pi if\theta}\sin\pi f\theta\right\rangle^2\frac{\left\langle e^{2\pi if\theta}\right\rangle}{1-\left\langle e^{2\pi if\theta}\right\rangle}\right\}.\qquad(9)$$

Out of the formula (9) we directly proceed to the expression for the fluctuations spectrum of the current that flows in the semiconductor under constant voltage applied to the sample. As the current is proportional to the number of free carriers in the sample, the spectrum of normalized current fluctuations in the semiconductor is as follows:

$$\frac{S\left(f\right)}{I^2}=\frac{1}{\langle N\rangle^2\pi^2f^2\langle\theta\rangle}\left\{\left\langle\delta N^2\sin^2\pi f\theta\right\rangle+\right.$$

$$+2\,\mathrm{Re}\left\langle\delta N_j\delta N_{j+1}e^{\pi if\left(\theta_j+\theta_{j+1}\right)}\sin\pi f\theta_j\sin\pi f\theta_{j+1}\right\rangle+$$

$$\left.+2\,\mathrm{Re}\left\langle\delta Ne^{\pi if\theta}\sin\pi f\theta\right\rangle^2\frac{\left\langle e^{2\pi if\theta}\right\rangle}{1-\left\langle e^{2\pi if\theta}\right\rangle}\right\}.\qquad(10)$$

Thus, we have examined the electrical fluctuations in semiconductors caused by stochastic processes of capture and emission of charge carriers by structural defects. The calculated general formula of the fluctuation spectrum can be used in the description of excess, generation-recombination and bursts noises. By defining the relations between the fluctuation process parameters and time distributions characteristic of a particular type of noise, we can deduce the formula of this noise's spectrum out of the general formula (10). In specific situations, by analyzing electrical fluctuations in solid bodies and solid-state electronic devices we can identify the spectral characteristics of the fluctuations by using the general formula (10) and defining the characteristics of the solid material and the parameters of the fluctuation process. The findings regarding the electrical fluctuations caused by capture and emission of charge carriers by structural defects can be used for identifying the spectral properties of fluctuations in solid bodies and solid-state electronic devices, as well as establishing the relations between the spectral properties and the characteristics of solid materials.

## Degradation processes

Let us analyze the degradation processes that occur in solid materials and solid-state electronic devices. The relevance of such research is due to the following. There is a group of electrical noises, of which the origins are due to structural defects of solid materials. The spectral properties of such noises depend on the degree of structural defect. A rigorous quantitative analysis would allow establishing associations between the spectral characteristics of noises with the degree of materials defectiveness and thus would allow using the noises in the evaluation of the quality and dependability of electronic devices.

Let us examine a degradation processes that occurs in a solid material. The result of this process is the increased number of structural defects. The number of defects increases with time. Broadly speaking, events of appearance and destruction of defects are possible. In other words, structural degradations are a stochastic process of defect number change. Such stochastic process can only assume non-negative values, process changes can occur at any moment in time $t$. At any moment it can either increase by 1 or decrease by 1 or remain unchanged. A stochastic process of this type is described with a system of Kolmogorov differential equations [12]:

$$\frac{dp_0(t)}{dt}=u_1(t)p_1(t)-w_0(t)p_0(t)$$

$$\frac{dp_1(t)}{dt}=w_0(t)p_0(t)+u_2(t)p_2(t)-\left(w_1(t)+u_1(t)\right)p_1(t)$$

...

$$\frac{dp_i(t)}{dt}=w_{i-1}(t)p_{i-1}(t)+u_{i+1}(t)p_{i+1}(t)-\left(w_i(t)+u_i(t)\right)p_i(t), \quad (11)$$

where $i = 1, 2, 3,\dots, p_i(t)$ is the probability of the number $i$ of structural defects at the moment of time $t$, $w_i(t)$ is the rate of occurrence of the events causing the increase of the number of defects, $u_i(t)$ is the rate of occurrence of the events causing the decrease of the number of defects. Let us find the average number of defects $N_d(t)$ at the moment of time $t$. Let us do that as follows. Let us multiply the left and right parts of the $i^{th}$ equation of the system (11) by the value $i$:

$$\frac{dp_1(t)}{dt}=w_0(t)p_0(t)+u_2(t)p_2(t)-\left(w_1(t)+u_1(t)\right)p_1(t)$$

...

$$i\frac{dp_i(t)}{dt}=iw_{i-1}(t)p_{i-1}(t)+iu_{i+1}(t)p_{i+1}(t)-i\left(w_i(t)+u_i(t)\right)p_i(t). \quad (12)$$

Let us combine the left and right parts of the resulting equations:

$$\sum_{i=1}^{\infty}i\frac{dp_i(t)}{dt}=\sum_{i=1}^{\infty}\begin{bmatrix}iw_{i-1}(t)p_{i-1}(t)+iu_{i+1}(t)p_{i+1}(t)-\\ -i\left(w_i(t)+u_i(t)\right)p_i(t)\end{bmatrix}. \quad (13)$$

Let us transform the left part of the equation:

$$\sum_{i=1}^{\infty}i\frac{dp_i(t)}{dt}=\frac{d}{dt}\sum_{i=1}^{\infty}ip_i(t)=\frac{d}{dt}N_d(t). \quad (14)$$

Let us have regard for the formulas:

$$\sum_{i=1}^{\infty}iw_{i-1}(t)p_{i-1}(t)=\sum_{i=1}^{\infty}(i+1)w_i(t)p_i(t), \quad (15)$$

$$\sum_{i=1}^{\infty}iu_{i+1}(t)p_{i+1}(t)=\sum_{i=1}^{\infty}(i-1)u_i(t)p_i(t). \quad (16)$$

As the result we obtain:

$$\frac{dN_d(t)}{dt}=\sum_{i=1}^{\infty}\left(w_i(t)-u_i(t)\right)p(t). \quad (17)$$

Real degradation processes occurring in solid bodies are normally characterized by the formula $w_i(t)=w(t)$ which means that the defect rate depends on the time and not the number of defects at the current moment. As under realistic defect concentrations the defects do not influence each other, the formula $u_i(t)=iu(t)$ is fulfilled, where $u(t)$ is the rate of occurrence for one defect, while the value $u(t)$ is usually quite small. Given that:

$$\sum_{i=1}^{\infty}w_i(t)p_i(t)=w(t)\sum_{i=1}^{\infty}p_i(t)=w(t), \quad (18)$$

$$\sum_{i=1}^{\infty}u_i(t)p_i(t)=u(t)\sum_{i=1}^{\infty}ip_i(t)=u(t)N_d(t). \quad (19)$$

Finally, we deduce the formula for $N_d(t)$:

$$\frac{dN_d(t)}{dt}=w(t)-u(t)N_d(t). \quad (20)$$

Its solution under the initial condition $N_d(0)$ is as follows:

$$N_d(t)=e^{-\int_0^t u(\theta)d\theta}\left[\int_0^t w(x)e^{\int_0^x u(\theta)d\theta}dx+N_d(0)\right]. \quad (21)$$

As the spectral density of the noises caused by structural defects is directly linked with the number of defects [1-3, 5], then using the formula (21) we can make the following conclusions. The spectral density of noise depends on the number of defects and, therefore, is linked to the degree of structural degradation. The spectral density of noise depends on the defect rate and, therefore, on the structural degradation rate. Thus, the noises in solid-state electronic devices contain information on the degree and rate of degradation. Below are the practical conclusions. The noise spectral density is associated with the number of defects in the device at the baseline, and, therefore, characterizes the quality of the manufactured device. Additionally, the spectral density of noise depends on the defect rate and, therefore, on the ageing rate of the electronic device. Thus, the spectral density of noise is linked with the device's operational characteristics change rate. Accordingly, the noise spectrum can be used in evaluation of an electronic device's deficiencies, both those occurring during the manufacturing process, and those that manifest themselves in operation.

## Conclusion

The paper analyzed the electric fluctuations in solid materials and solid-state electronic devices caused by defects. A quantitative description of fluctuation was provided. A general expression for the fluctuation spectrum was calculated. The findings can be used in the description of excess, generation-recombination and bursts noises. The noises of those types are fundamental and largely define the appearance of the spectrum and intensity of noise in many electronic devices. Those noises are largely associated with the defects of solid materials and can be widely used for nondestructive quality testing of solid-state electronics. The findings set forth in the article enable a simple identification of the spectral properties of and intensity of noises caused by defects in various electronic devices.

Degradation processes that occur in solid-state electronic devices were analyzed. The quantitative characteristics of the degradation processes were identified. The connection between the electrical noises caused by defects and both the degree and rate of degradation processes in electronic devices were shown. It was established that the noise spectrum contains information on electronic devices' deficiencies, both those occurring during the manufacturing process, and those that manifest themselves in operation. The paper substantiates the potential wide applications of electrical noises in nondestructive testing of electronic devices, shows the feasibility of using fundamental types of electrical noises for the above purposes. The rigorous substantiation of the use of electrical noises for nondestructive testing of electronic devices, feasibility of evaluation of the devices' defects caused by various factors, use of common frequently prevailing types of noise, high sensitivity of fluctuation spectroscopy highlight the efficiency of electrical noise in nondestructive testing of electronic devices.

## References


1. Jones BK. Electrical noise as a measure of quality and reliability in electronic devices. Adv. Electron. Electron. Phys. 1993;87:201-257.

2. Yakubovich BI. Elektricheskiy shum i defekty struktury tverdykh tel [Electrical noise and structure defects in solids]. Germany: LAP Lambert Academic Publishing; 2012.

3. Kirton MJ, Uren MJ. Noise in solid-state microstructures: A new perspective on individual defects, interface states and low-frequency (1/f) noise. J. Adv. Phys. 1989;38(4):367-468.

4. Fleetwood DM. 1/f noise and defects in microelectronic materials and devices. IEEE Trans. Nucl. Sci. 2015;62(4):1462-1486.

5. Yakubovich BI. Elektricheskie fluktuatsii v tverdykh telakh [Electrical fluctuations in solids]. Germany: AV Akademikerverlag; 2013.

6. Malakhov AN. K voprosu o spektre flikker-shuma [More on the jitter noise]. Radiotekhnika i elektronika 1959;4(1):54-62 [in Russian].

7. Yakubovich BI. Elektricheskie fluktuatsii v nemetallakh [Electrical fluctuations in non-metals]. Saint-Petersburg: Energoatomizdat; 2006.

8. Yakubovich BI. O prirode izbytochnogo nizkochastotnogo shuma (obzor) [On the nature of excessive low-frequency noise (an overview)]. Ouspekhi prikladnoi fiziki 2016;4(2):127-138 [in Russian].

9. Mitin V, Reggiani L, Varani L. Balandin A, editor. Generation-recombination noise in semiconductors. Noise and fluctuations control in electronic devices. California: American scientific publishers; 2002.

10. Yakubovich BI. Generatsionno-rekombinatsionnyi shum v poluprovodnikakh [Generation-recombination noise in semiconductors]. Naouchnoie priborostroenie 2013;23(4):50-53 [in Russian].

11. Kleinpenning TGM. On 1/f noise and random telegraph noise in very small electronic devices. Physica B. 1990;164(3):331-334.

12. Feller W. An introduction to probability theory and its applications. Volume 1. Moscow: Mir; 1984.


## About the authors


**Boris I. Yakubovich,** Candidate of Physics and Mathematics, Senior Researcher, Saint Petersburg Institute of Nuclear Physics, National Research Center Kurchatov Institute, Orlova roshcha, 188300 Gatchina, Leningrad Oblast, Russia, tel.: 81371 4 64 92, e-mail: yakubovich_bi@pnpi.nrcki.ru


**Received on 23.03.2017**

Original article
DOI: 10.21683/1729-2646-2017-17-2-36-40

# Functional dependability of the display unit software of the BLOK system

**Efim N. Rozenberg,** *JSC NIIAS, Moscow, Russia*
**Natalia G. Penkova,** *JSC NIIAS, Moscow, Russia*
**Alexander S. Korovin,** *JSC NIIAS, Moscow, Russia*


*Efim N. Rozenberg*


*Natalia G. Penkova*


*Alexander S. Korovin*

**Abstract. Aim.** *The article is dedicated to the challenges of evaluating the functional dependability of the display unit software (SW) that is part of the BLOK vital integrated onboard system as attributed to program errors within a 24-hour target time. One of the key tasks is the calculation of the values of such SW functional dependability characteristics as accuracy, correctness, security, controllability, reliability, fault tolerance and availability, which are the primary indicators for evaluating the health of safety devices. With all this taken into account, it is to be evaluated whether the checking of the software of the display unit before each trip with a departure test is required.* **Method.** *The reference conditions do not contain statistical data of program executions over the course of its maintenance. There is also no information on the structural characteristics of the program (number of operators, operands, cycles, etc.) which prevents the use of statistical models of dependability, such as the Halstead metrics, IBM model or similar ones. That is why the Schumann model was chosen as the initial data definition apparatus. The method of evaluation of the display unit's functional dependability is based on the findings of [1].* **Results.** *At the first stage, the following initial data values were defined: initial number of defects in the program, program failure rate and probability of correct run. At the subsequent stage, the identified values were used to define such dependability parameters as probability of no-error as the result of program run within a given time, probability of no-failure of display unit as the result of program run within a given time and mean time to program failure. After the probability $P_{SW}(t)$ of no-error as the result of program run within a given time was calculated, such SW dependability attributes as accuracy, correctness, security and controllability were evaluated. After the probability of no-failure of the display unit $P_R(t)$ as the result of program run within a given time was calculated, an evaluation was given to such attributes as SW reliability and fault tolerance, while after the mean time to program failure $T_{avSW}$ was calculated, knowing the mean downtime due to elimination of the program error $\tau_{pdt}$, the display unit availability for faultless execution of an information process at an arbitrary point in time $C_{fa}$ was defined. The calculated partial functional availability coefficients for the display unit have shown that pre-trip checking of the unit and immediate elimination of errors, should such be identified, will enable a significant improvement of user performance of the onboard display unit (BIL) in terms of timely notification of the driver on the current operational situation to enable timely train control decision-making.*

**Keywords:** *BLOK Vital Integrated Onboard System, display unit, functional dependability.*

**For citation:** *Rozenberg EN, Penkova NG, Korovin AS. Functional dependability of the display unit software of the BLOK system. Dependability 2017; 2: 36-40. DOI: 10.21683/1729-2646-2017-17-2-36-40*

The Vital Integrated Onboard System (BLOK) is an advanced onboard train protection solution that is widely deployed on the Russian railway network. BLOK replaces and integrates the functionalities of such onboard safety devices as KLUB (Integrated Onboard Safety Device), SAUT (Automatic Brake Control System) and TSKBM (Remote Driver Vigilance Supervision System).

BLOK is designed to ensure train protection on lines with autonomous and electric traction equipped with trackside devices of the ALSN (continuous automatic cab signalling with digital coding), ALS-EN (multiaspect continuous automatic cab signalling with phase difference modulation of the carrier frequency) and SAUT systems, digital radio, discrete communication devices, coordinate-based train separation systems, as well as lines equipped with semi-automatic block devices.

A significant role in ensuring traffic safety is given to man-machine interaction that is provided by information display and control devices. The BLOK system includes a display unit. The unit displays all the required information on the operational situation along the line and operation of the onboard equipment, which enable the driver to successfully solve problems, should such arise.

Let us consider an example of evaluation of functional dependability of the display unit software that is part of the BLOK vital integrated onboard system.

## Results of display unit software testing

The display unit software is designed to display operational situation to the driver in real time.

The software was tested at the debugging stage. The connection of the display unit is shown in the structural diagram in Figure 1.

The structural chart includes:

- power supply unit;
- onboard display unit (BIL);
- personal computer with simulation software;
- Kvaser, USB to CAN (Controller Area Network) interface converter.

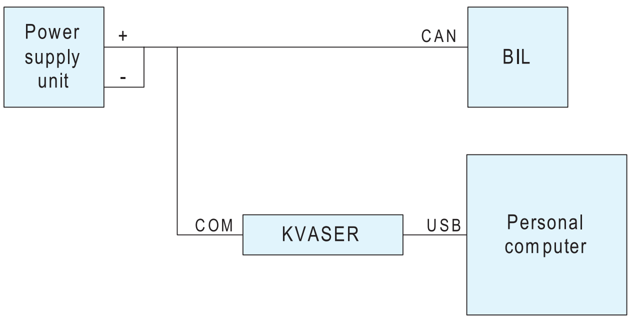



Fig. 1

Program execution requests arrive with the rate of $\gamma$ = 1800 1/h from the simulation software installed on the personal computer.

14 stages of testing were performed:

1. Testing of signal aspect display based on ALSN data along with testing of correct ALSN frequency display.

For 7 hours the simulation program was sending to the display unit CAN messages of alternating signal aspects per ALSN (the signal aspects are white, red, red and yellow, yellow, green) and alternating frequencies per ALSN (the frequencies are 25 Hz, 50 Hz, 75 Hz, 25 Hz). The results of this stage of testing did not indicate any program error.

2. Testing of signal aspect display based on ALS-EN data along with testing of correct display of movement ahead or with deviation.

For 7 hours the simulation program was sending to the display unit CAN messages of alternating signal aspects per ALS-EN (the signal aspects are white, flashing, red, red and yellow, 1TC, 2TC, 3TC, 4TC, 5TC) and alternating movement directions ahead and with deviation (the values are none, ahead, with deviation). At this stage of testing, two errors were identified: when signal aspect per ALS-EN is red and yellow or red, the display unit displays movement ahead or with deviation incorrectly.

3. Verification of correct display of actual, target and allowed speeds.

For 8 hours the simulation program was sending to the display unit messages of actual, target and allowed speed values. Assigned values of actual speed: 0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 120, 0. Assigned values of target speed: 0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 200. Assigned values of allowed speed: 0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 0). The results of this stage of testing did not indicate any program error.

4. Verification of correct display of the coordinate, track number, movement direction forward or backward.

For 9 hours the simulation program was sending to the display unit CAN messages of the coordinates (0 km 0 kp 1 m, 4 km 5 kp 99 m, 9999 km 9 kp 99 m, 0 km 0 kp 0 m), track number values (0, 8, 15, 1), movement direction values (forward, backward). The results of this stage of testing did not indicate any program error.

5. Verification of correct display of the target name, type and distance, as well as station name.

For 9 hours the simulation program was sending to the display unit CAN messages of target names (Iksha, Nakhabino, none), target types (signal, station, hazardous place, bridge, level crossing, platform, tunnel, switch, track circuit, SAUT discrete channel transceiver, siding, tail of train, stop location, work area, conditionally clear signal, station), distances to targets (1 m, 1000 m, 8191 m, 0 m) and station names (Moscow, Tushino, Bolevoue, none). The results of this stage of testing did not indicate any program error.

6. Verification of correct display of pressure in the brake cylinder, brake line and control reservoir.

For 7 hours the simulation program was sending to the display unit CAN messages of the brake cylinder pressure (0.1 MPa, 0.5 MPa, 1.0 MPa, 0 MPa), brake line pressure (0.1 MPa, 0.5 MPa, 1.0 MPa, 0 MPa) and control reservoir pressure (0.1 MPa, 0.5 MPa, 1.0 MPa, 0 MPa). The results of this stage of testing did not indicate any program error.

7. Generation by the display unit of CAN messages on the program operability.

For 10 hours the simulation program verified the generation (every 500 ms) by the display unit of CAN messages on the program operability. At this testing stage two errors were identified and the display unit restarted the software twice and resumed the generation every 500 ms of CAN messages on the operability.

8. Verification of correct display of automatic train operation (ATO) mode, ATO target speed value, ATO schedule time.

For 9 hours the simulation program was sending to the display unit CAN messages of ATO mode values (ATO off, ATO in advisory mode, ATO in automatic mode), ATO target speed values (0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 120, 0), ATO schedule time values (0 hours 10 minutes 15 seconds; 3 hours 12 minutes 19 seconds; 5 hours 19 minutes 22 seconds; 11 hours 23 minutes 27 seconds; 15 hours 27 minutes 34 seconds; 19 hours 34 minutes 38 seconds; 22 hours 44 minutes 47 seconds; 23 hours 57 minutes 59 seconds). The results of this stage of testing did not indicate any program error.

9. Verification of correct display of preliminary signalling, preliminary TSKBM signalling, driver vigilance confirmation request and stability of radio communication.

For 7 hours the simulation program was sending to the display unit CAN messages of the preliminary signalling value (on, off), TSKBM preliminary signalling value (on, off), driver vigilance confirmation request value (request, no request) and radio communication stability value (availability of communication, non-availability of communication). The results of this stage of testing did not indicate any program error.

10. Verification of correct display of acceleration, presence of neutral/dead section and distance to neutral/dead section.

For 9 hours the simulation program was sending to the display unit CAN messages of the acceleration values (-1,0, -0,92, -0,80, -0,73, -0,69, -0,53, -0,44, -0,30, -0,22, -0,10, -0,02, 0,04, 0,15, 0,23, 0,37, 0,49, 0,56, 0,66, 0,79, 0,83, 0,94, 1,0), presence of neutral/dead section values (no neutral or dead section, neutral section present, dead section present), distance to neutral/dead section values (0 m, 140 m, 631 m, 1202 m, 3044 m, 9999 m, 42142 m, 65535 m). The results of this stage of testing did not indicate any program error.

11. Verification of correct command input in the display unit data line.

For 8 hours the display unit keyboard was used to input data line commands (C0, C5, C6, C7, C71, C70, C91, C92, C261, C517, C522, C773, C799, C809, C800, C1029, C2565). The results of this stage of testing did not indicate any program error.

12. Verification of correct display of diagnostics messages in the display unit's data line.

For 7 hours the simulation program was sending to the display unit CAN messages of the following diagnostics messages: trip. KON, trip. EPV TSKBM, trip. EPV SAUT, slippage, electronic map number, display of the presence of BLOK modules in the configuration, display of the version, subversion and BLOK modules checksums). The results of this stage of testing did not indicate any program error.

**Table 1.**

| Number of testing stage | Duration of testing stage *t*, h | Number of identified program errors *m* |
|---|---|---|
| 1 | 7 | 0 |
| 2 | 7 | 2 |
| 3 | 8 | 0 |
| 4 | 9 | 0 |
| 5 | 8 | 0 |
| 6 | 7 | 0 |
| 7 | 10 | 2 |
| 8 | 9 | 0 |
| 9 | 7 | 0 |
| 10 | 7 | 0 |
| 11 | 8 | 0 |
| 12 | 7 | 0 |
| 13 | 7 | 0 |
| 14 | 7 | 0 |

13. Verification of correct display of current time.

For 7 hours the simulation program was sending to the display unit CAN messages of the current time values (0 hours 10 minutes 15 seconds; 3 hours 12 minutes 19 seconds; 5 hours 19 minutes 22 seconds; 11 hours 23 minutes 27 seconds; 15 hours 27 minutes 34 seconds; 19 hours 34 minutes 38 seconds; 22 hours 44 minutes 47 seconds; 23 hours 57 minutes 59 seconds). The results of this stage of testing did not indicate any program error.

14. Verification of correct display of recorder unit status and operating mode.

For 7 hours the simulation program was sending to the display unit messages of recorder unit status value (present, absent) and operating mode values (main-line, shunting, double heading). The results of this stage of testing did not indicate any program error.

The results of test stages are given in Table 1.

## Reference conditions for calculation of display unit software dependability

Beside the test results described above the BIL software dependability indicators calculation involves the following initial data. The probability of SW error causing unit failure, $g_{ft} = 0,047$ [1]. The failure rate of the display unit's hardware components is $\lambda_{hw} = 3,01 \cdot 10^{-6}$ 1/h [4]. A self-test subprogram is assumed to be available with a failure detection probability at around $\alpha = 0,5$ [3]. Same goes for the failure response mechanisms with the probability of successful mitigation of an identified functional failure of $\beta = 0,99$.

$$\beta = 1 - \lambda_{hw} * t,$$

where $\lambda_{hw}$ is the failure rate of the display unit's hardware components;

$t$ is the target time of system operation.

The average downtime of the display unit caused by the required elimination of software error is $\tau_{dt} = 24$ h.

It is required to calculate the unit's dependability indicators as regards software errors under the target system operation time $t = 24$ h on the assumption of the absence of fault-inducing errors, a well as on the assumption that with the correction of identified errors no new defects are introduced in the software.

## Calculation of display unit software dependability indicators

The reference conditions do not contain statistical data of program executions over the course of its maintenance. There is also no information on the structural characteristics of the program (number of operators, operands, cycles, etc.) which prevents the use of statistical models of dependability, such as the Halstead metrics, IBM model or similar ones. Therefore, let us choose the solution based on the Schumann model. Meaning, let us find the initial number of software defects, then the error rate and values of unknown probability values that describe the SW dependability indicators.

The initial number of software defects $N$ is calculated using the following equation:

$$\sum_{j=1}^{k} m_j \cdot \frac{\sum_{j=1}^{k} t_j}{\sum_{j=1}^{k} \frac{m_j}{N-n_{j-1}}} = \sum_{j=1}^{k} (N-n_{j-1}) t_j ,$$

where $k$ = 14 (number of testing stages);

$m_j$ is the number of identified software errors at the $j^{th}$ testing stage;

$n_j = m_1 + m_2 + \ldots + m_j$ is the total number of identified software errors at the 1-$j^{th}$ testing stage;

$t_j$ is the duration of the $j^{th}$ testing stage.

Values $m_j$, $n_j$ and $t_j$ are given in Table 1. In accordance with those values, by means of the trail and error method, $N = 7$ was deduced.

The software error rate $\lambda_{sw}$ is calculated using the Schumann formula

$$\lambda_{sw} = \frac{\sum_{j=1}^{k} \frac{m_j}{N-n_{j-1}}}{\sum_{j=1}^{k} t_j} \left(N - n_k\right)$$

Given the values of variables calculated at the previous step, $\lambda_{sw}$ is

The probability of correct program run $P_{sw\,run}$ after troubleshooting is calculated using the formula

$$P_{sw\,run} = \frac{1-\frac{\lambda_{sw}}{\gamma}}{P_n} = \frac{1-\frac{0,014}{1800}}{1} = 1 - 7,77\ \ 10^{-6} = 0,99999,$$

where $P_c$ is the probability of absence of fault-inducing errors that, assuming there are no such errors (see section Initial data), equals to 1.

Now let us define the unit's dependability indicators as attributed to software errors within a 24-hour target time.

The probability $P_{sw}(t)$ of no-error as the result of program run within the given time $t$ = 24 h.

$$P_{sw}\left(t\right) = \exp\left(-\lambda_{sw} t\right) = \exp\left(-24 \cdot 0,014\right) \approx 0.7.$$

Mean time to software error $T_{av\,sw}$

$$T_{avsw} = \frac{1}{\lambda_{sw}} = \frac{1}{0.014} = 71,43\,h.$$

The probability of no-failure of display unit $P_R$(t) as the result of program run within the given time $t$ = 24 h.

$$P_R\left(t\right) = \exp\left(-\lambda_{hw} t\right)[1-(1-\alpha\beta)g_{ft}(1-\exp(-\lambda_{sw} t))] =$$
$$= \exp\left(-24 \cdot 3,01 \cdot 10^{-6}\right) \cdot [1-(1-0,5 \cdot 0,99) \cdot 0,047 \cdot$$
$$\cdot (1-\exp(-24 \cdot 0,014))] = 0,99.$$

Mean time to partial functional failure of display unit $T_{av\,un}$

$$T_{av\,un} = \frac{1-g_{ft}(1+\alpha\beta\ )}{\lambda_{hw}} + \frac{g_{ft}(1+\alpha\beta)}{\lambda_{sw}+\lambda_{hw}} =$$
$$= \frac{1-0,047\cdot(1+0,5\cdot 0,99)}{3,01\cdot 10^{-6}} +$$
$$+ \frac{1-0,047\cdot(1+0,5\cdot 0,99)}{0,014+3,01\cdot 10^{-6}} = 3,08\cdot 10^5\ h.$$

Partial functional availability factor of display unit

$$C_{fa} = \frac{T_{av\,hw}}{T_{av\,sw}+\tau_{pdt}} = \frac{71,43}{71,43+24} = 0,749.$$

As the result of benchmark tests of the display unit software at the troubleshooting stage several errors were identified. However, it cannot be ruled out that the operation of the software in actual use environment will not uncover other errors. Therefore, it is advisable to check the display unit software before each trip and immediately eliminate identified errors should the departure test indicate the presence of such. If systematic, this procedure will significantly improve the availability of BLOK. For instance, reducing the error elimination time from 24 to 1 hour through timely elimination of identified failures ($\tau_{pdt}$ = 1 h) enables a display unit partial functional availability indicator equal to

$$C_{fa} = \frac{T_{av\,sw}}{T_{av\,sw}+\tau_{pdt}} = \frac{71,43}{71,43+1} = 0,986.$$

Thus, if the software error elimination time is $\tau_{pdt}$ = 24 h, the display unit partial functional availability equals to $C_{fa}$ = 0,749, while the reduction of the error elimination time to $\tau_{pdt}$ = 1 h enables the display unit partial functional availability value equal to $C_{fa}$ = 0,986, which practically improves the BIL SW operating characteristics by 25 percent.

## Conclusion

The article considered an example of evaluation of functional dependability of the display unit software that is part of the BLOK vital integrated onboard system. The example of this isolated case shows that the chosen method is effective and can be used in practice.

The resultant partial functional availability indicators of the display unit show that pre-trip checking of the unit and immediate elimination of errors, should such be identified, will enable a significant improvement of user performance of BIL in terms of timely notification of the driver on the current operational situation to enable timely train control decision-making.

## Acknowledgement

The authors express their gratitude to Prof. Igor B. Shubinsky, Doctor of Engineering, for his assistance, valuable advice and observations that contributed to this paper.

## References

1. Shubinsky IB. Funktsionalnaia nadiozhnost informatsionnykh system. Metody analiza [Functional reliability of information systems. Analysis methods]. Dependability Journal LLC 2012 [in Russian].

2. Shukhina EE, Astrakhan VI. Bezopasni lokomotivni obiedinenni kompleks BLOK [BLOK Vital Integrated Onboard System]. Moscow; 2013 [in Russian].

3. GOST R IEC 61508–7–2012. Functional safety of electrical, electronic, programmable electronic safety-related systems. Part 7: Overview of techniques and measures.

4. Explanatory note with the display unit dependability calculation.

## About the authors

**Efim N. Rozenberg**, Professor, Doctor of Engineering, First Deputy Director General, JSC NIIAS. 27, bldg 1 Nizhegorodskaya St., 109029 Moscow, Russia, phone: +7 (499) 262 62 17, e-mail: info@vniias.ru

**Natalia G. Penkova**, Deputy Head of Safety and Algorithmic Support, JSC NIIAS. 27, bldg 1 Nizhegorodskaya St., 109029 Moscow, Russia, phone: +7 (499) 260 77 52, e-mail: N.Penkova@vniias.ru

**Alexander S. Korovin**, Chief Specialist of Computer-Based Devices Development, JSC NIIAS. 27, bldg 1 Nizhegorodskaya St., 109029 Moscow, Russia, phone: +7 (499) 262 82 53, e-mail: A.Korovin@vniias.ru

**Received on 06.12.2016**

# A model of function-level fault tolerance of navigation signals provision processes in adverse conditions

**Sergey M. Klimov**, *4th Central Research and Design Institute of the Ministry of Defence of Russia, Korolyov, Russia*
**Aleksey Yu. Polovnikov**, *4th Central Research and Design Institute of the Ministry of Defence of Russia, Korolyov, Russia*
**Aleksey P. Sergeev**, *4th Central Research and Design Institute of the Ministry of Defence of Russia, Korolyov, Russia*

Sergey M. Klimov

Aleksey Yu. Polovnikov

Aleksey P. Sergeev

**Abstract.** *The aim of this article is to develop a model that would allow quantitatively evaluating the function-level fault tolerance of navigation signals provision processes in adverse reception conditions using consumer navigation equipment (CNE). The article also substantiates the relevance and importance of evaluation of the function-level fault tolerance of consumer navigation systems in those cases when the reception of the signals is affected by industrial interference, pseudo-satellites, rereflections from urban structures and terrain features. The function-level fault tolerance of the processes of navigation signals (of CNE) provision to consumers in adverse conditions is understood as their ability to fulfil their functions and retain the allowed parameter values under information technology interference within a given time period. The adverse conditions of provision of navigation data (signals) to consumers are understood as a set of undesirable events and statuses of reception and processing of navigation data with possible distortions. The article analyzes a standard certificate of vulnerabilities of navigation signal (by the example of distortion of pseudorange and pseudovelocity values distortion) that defines the input data for the analysis of CNE equipment fault tolerance. The model is based on the following approaches: the navigation signal parameters are pseudorange and pseudovelocity, system almanac data and ephemeris information; quantitative evaluation of function-level fault tolerance of the processes of navigation signals provision to users is based on the probability of no-failure of CNE in adverse conditions; function-level fault tolerance of the above processes is ensured by means of integrated use of functional, hardware, software and time redundancy; the hardware and software structure of the CNE fault tolerance facilities has the form of a three-element hot and cold standby system; the allowable level of function-level fault tolerance violation risk is defined according to the ALARP principle. It is shown that CNE fault tolerance and jamming resistance is based on the following: use of multisystem navigation receivers; navigation signal integrity supervision; spatial and frequency-time selection of signal; precorrelation processing of signal and interference mixture; postcorrelation signal processing; processing of radio-frequency and information parameters of the signal; cryptographic authentication; integration with external sources of navigation information and within a single signal processing system of a number of methods of interference countermeasures and pseudo-satellite navigation signals. The proposed model defines the CNE function-level fault tolerance as two variants of dynamic dependability models, in which the values of probability of no-failure are time-dependent: a hot standby system that includes three additional countermeasure modules and a cold standby system with a switch to three additional countermeasures modules. The model allows visualizing the processes of navigation signals provision to users in adverse conditions, quantitatively evaluating the probability of no-failure for hot and cold standby systems with three modules of information technology interference countermeasures, probability of recovery and CNE availability coefficient, as well as the allowable risk of CNE fault tolerance violation.*

**Keywords:** *navigation signals consumer, consumer navigation equipment, adverse conditions, function-level fault-tolerance, probability of no-failure.*

**For citation:** *Klimov SM, Polovnikov AYu, Sergeev AP. A model of function-level fault tolerance of navigation signals provision processes in adverse conditions. Dependability,2017;2: 41-47. DOI: 10.21683/1729-2646-2017-17-2-41-47*

## Introduction

Currently, it is required to expand the application of services based on the GLONASS satellite radionavigation system (SRNS) both for national consumers and international application of Russian satellite navigation technology [1]. One of the key tasks of GLONASS development is to support the competitive performance of its guaranteed navigation field and further improve the system in terms of its consumer properties (most importantly, positioning accuracy).

The GOST R 52865-2009 standard defines the "satellite radionavigation system navigation field" as a set of radionavigation signals in the SRNS operating area that enables the measurement of navigation parameters and identification of the position and time of the consumer with the required level of availability, dependability and accuracy. Therefore, the navigation field is a set of radio signals at the input of the ground-based consumer equipment (CNE) that enables navigation and time definitions. A state-of-the-art CNE can be considered as a specialized computer system for collection, processing and output of navigation data to the consumer.

In the actual and complex conditions of GLONASS application (comparable to those of foreign space-based navigation systems) the integrity and availability of the received navigation data (signals) in CNE can be disrupted, which causes errors in coordinate and consumer movement speed definition (e.g. land, maritime and air transport).

Potential integrity and availability violations of received digital navigation signals are due to random manifestations of unintentional or intentional defects in the special software in the process of GLONASS CNE operation under the following adverse interference conditions:

- man-made interference,
- distorted navigation signals (data) from pseudo-satellites (e.g. transmitted by unmanned aerial vehicles [2]),
- distorted navigation signals rereflected from urban structures or distorted due to signal reception on the Earth's surface with challenging terrain (presence of multipath effect, e.g. in mountainous areas).

The manifestations of such defects in complex interference conditions are essentially information technology interference (ITI) against digital navigation data (frames) that are received and processed by the CNE hardware and software.

The set of undesirable events and states of reception and processing of navigation data with possible distortions will be understood as adverse conditions of processes of navigation data (signals) provision to consumers. This article does not consider the disruptions of navigation data caused by conventional errors of CNE positioning.

In practice, the mentioned adverse conditions cause not only stability problems, but in some cases blocking of processes and non-fulfilment of functions related to provision of navigation data to consumers and operation of systems that use coordinate and time information.

The objective cause of distortion of navigation data (frames) received by the consumer is the long distance (over 19000 km) between the visible GLONASS constellation and the CNE equipment. The coordinate and time information transmitted by the spacecraft in the navigation frame and the actual measurements on the consumer's side on the Earth's surface differ due to the Doppler effect of radio waves deviation in the course of their propagation.

The function-level fault tolerance of the processes of navigation signals (of CNE facilities) provision to consumers in adverse conditions will be understood as their ability to fulfil their functions and retain the allowed parameter values under information technology interference within a given time period.

In order to measure the function-level fault tolerance of the processes of navigation signals provision to customers, it is required to test the CNE architecture in adverse conditions of operation up to the occurrence of faults (failures), and then, based on the test results, perform the processing of statistical data and calculations.

Thus, the development of a model that would allow quantitatively evaluate the function-level fault tolerance of the processes of navigation signals provision to consumers in adverse conditions of man-made interference, presence of pseudo-satellites and signal rereflections is relevant and of practical interest.

## Problem definition

The research is based on the following premises:

- the parameters of navigation signals are the pseudorange and pseudovelocity, as well as almanac data and ephemeris information of the navigation signal digital message [3];
- the quantitative evaluation of function-level fault tolerance of processes of navigation signals provision to customers is based on the probability of no-failure of CNE in adverse conditions;
- function-level fault tolerance of the above processes is ensured by multi-level redundancy (combination of functional, hardware, software and time redundancy) [4];
- the architecture of hardware and software facilities of CNE fault tolerance is seen as a three-element hot or cold standby system [5];
- the tolerable level of risk of CNE function-level fault-tolerance violation is defined according to the ALARP principle [4].

GLONASS onboard and CNE equipment are intended for the measurement of two initial navigation parameters, the distance between the satellite and the consumer $s$ and this distance's change rate $\dot{s}$. Assertions about the distance $s$ are made based on the signal propagation time from the satellite to the consumer, while assertions about the value $\dot{s}$ are made based on either the change of the signal $s$ in time, or the Doppler effect [6].

As in the real conditions the satellite's and consumer's clocks are not synchronized, the used method of determining the distance and its change rate introduces errors caused by independent errors of the satellite's and the consumer's clocks. For that reason the measurement results use the terms "pseudorange" and "pseudovelocity".

Based on the measured parameters $s$ and $\dot{s}$, as well as the satellite coordinates and velocity data from the almanac and ephemeris information, the coordinates and velocity of the consumer can be calculated using Newton's iteration method involving the following mathematical expressions:

$$s_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} + \Delta s_i, \quad (1)$$

$$\dot{s}_i = ((x_i - x)(Vx_i - Vx) + (y_i - y)(Vy_i - Vy) + \\ + (z_i - z)(Vz_i - Vz)) / s_i + \Delta \dot{s}_i, \quad (2)$$

where $x_i$, $y_i$, $z_i$ are the Greenwich orthogonal coordinates of the $i^{th}$ navigation satellite, $x$, $y$, $z$ are the Greenwich orthogonal coordinates of the consumer, $Vx_i$, $Vy_i$, $Vz_i$ are the velocity vector components of the $i^{th}$ navigation satellite, $Vx$, $Vy$, $Vz$ are the velocity vector components of the consumer, $\Delta s_i$ is the pseudorange measurement error, $\Delta \dot{s}_i$ is the pseudovelocity measurement error.

The processes of navigation signals provision to consumers are primarily implemented by the CNE hardware and software. In the simplest case, the analysis of the fault tolerance of the processes of navigation signals provision to consumers comes down to the CNE fault tolerance analysis.

The standard certificate of vulnerabilities of navigation signal (by the example of pseudorange and pseudovelocity values distortion) that defines the input data for the analysis of CNE fault tolerance is given in Table 1.

The CNE navigation data collection and processing hardware and software are a correlation receiver, of which the precorrelation pathway is coordinated with the useful signal bandwidth. The required CNE function-level fault tolerance in adverse conditions is to be achieved through multi-level redundancy (combination of functional, hardware, software and time redundancy) and the following methods of improving the CNE fault tolerance and jamming resistance:

- use of multisystem navigation receivers,
- navigation signal integrity supervision,
- spatial and frequency-time selection of signal,
- precorrelation processing of signal and interference mixture,
- postcorrelation signal processing,
- processing of radio-frequency parameters of the signal (e.g. signal strength control),
- processing of information parameters of the signal (e.g. code and phase measurements),
- cryptographic authentication,
- integration with external sources of navigation information,
- integration within a single signal processing system of a number of methods of interference countermeasures and pseudo-satellite navigation signals.

The diagram of the model of CNE function-level fault tolerance in adverse conditions is shown in Figure 1.

Figure 1 shows the standard states of the graph model of CNE function-level fault tolerance:

**Table 1. Standard certificate of vulnerabilities of navigation signal (by the example of pseudorange and pseudovelocity values distortion)**

| Vulnerability description elements | Vulnerability description |
|---|---|
| 1. Name of vulnerability | CNE vulnerability |
| 2. Vulnerability identifier | NAP-2017-00003 |
| 3. Brief description of vulnerability | Vulnerability allows distortion of pseudorange and pseudovelocity |
| 4. Vulnerability class | Software vulnerability |
| 5. Name of vulnerable element | CNE computer module |
| 6. Data communication protocol | Standard accuracy navigation radio signal |
| 7. Type of defect | Stadiometric code defects |
| 8. Location of occurrence (manifestation) of vulnerability | Vulnerability exists due to periodicity of pseudorandom stadiometric code |
| 9. Date of vulnerability detection | 10.02.2017 |
| 10. Author of information on detected vulnerability | Information security unit |
| 11. Method (rule) of vulnerability detection | Execution of step-by-step instructions |
| 12. Vulnerability hazard criteria | Exceeding of set values of accuracy characteristics |
| 13. Hazard level of vulnerability | High |
| 14. Possible vulnerability elimination measures | Introduction of functional, hardware, software and time redundancy in the CNE equipment |

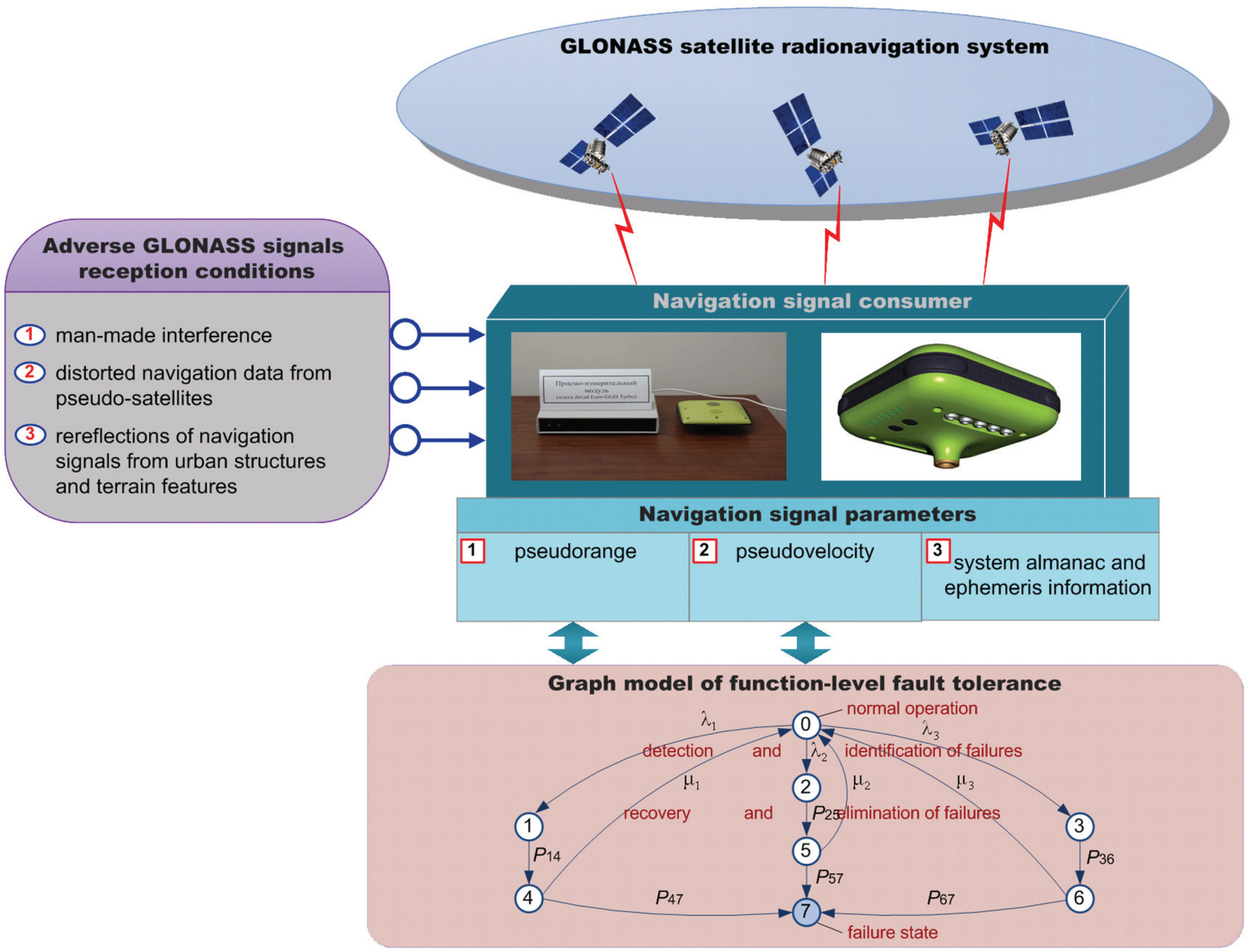



Figure 1. Diagram of the model of CNE function-level fault tolerance in adverse conditions

0 – CNE modules operate in the normal mode with no failures;

1 – failure (fault) of CNE due to man-made interference with the rate of $\lambda_1$;

2 – failure (fault) of CNE due to distorted navigation signals (data) from pseudo-satellites with the rate of $\lambda_2$;

3 – failure (fault) of CNE due to distorted navigation signals rereflected from urban structures or terrain features with the rate of $\lambda_3$;

4 – recovery and elimination of CNE failure (fault) by the man-made interference countermeasures module with the probability of $p_{14}$;

5 – recovery and elimination of CNE failure (fault) by the pseudo-satellite navigation signals (data) countermeasures module with the probability of $p_{25}$;

6 – recovery and elimination of CNE failure (fault) by the rereflected navigation signals (data) from urban structures and terrain features countermeasures module with the probability of $p_{36}$;

7 – hazardous CNE failure due to non-operation of one of the above recovery and failure elimination modules (states 4 – 5) with the respective probabilities of $p_{47}$, $p_{57}$ and $p_{67}$.

Expected mathematic correlations of CNE function-level fault tolerance model.

Let us consider the above model of CNE function-level fault tolerance as two variants of dynamic dependability models [5], in which the values of probability of no-failure are time-dependent:

First variant, a hot standby system that includes three additional countermeasure modules.

Second variant, a cold standby system with a switch to three additional countermeasures modules.

Both variants allow for cases when each of the countermeasures modules has an exponential failure law of CNE.

First variant. We interpret the model of CNE function-level fault-tolerance with the hot standby system with three additional countermeasures modules (relative to the general use CNE) that ensure equipment operability in the adverse conditions under investigation. In such hot standby system the three additional countermeasures modules are initially on, while system is able to operate even with a single module (in this case it is assumed the adverse conditions do not correlate with each other).

Then, assuming that there is no ITI in navigation signals, let us write the probability of no-failure of CNE (hot standby) in adverse conditions for three additional countermeasures modules using [5] as:

$$P_{CNE}^{HSB}(t) = e^{-t\lambda 1} + e^{-t\lambda 2} + e^{-t\lambda 3} - e^{-t(\lambda 1+\lambda 2)} - \\ - e^{-t(\lambda 1+\lambda 3)} - e^{-t(\lambda 2+\lambda 3)} + e^{-t(\lambda 1+\lambda 2+\lambda 3)}, \quad (3)$$

where $t$ is the time to failure of one of the CNE countermeasures modules.

Figure 2 shows the probability of no-failure of CNE (hot standby) in adverse conditions for three additional countermeasures modules under the following initial conditions: $\lambda_1 = 1{,}0{\cdot}10^{-8}$, $\lambda_2 = 1{,}0{\cdot}10^{-10}$, $\lambda_3 = 1{,}0{\cdot}10^{-6}$.

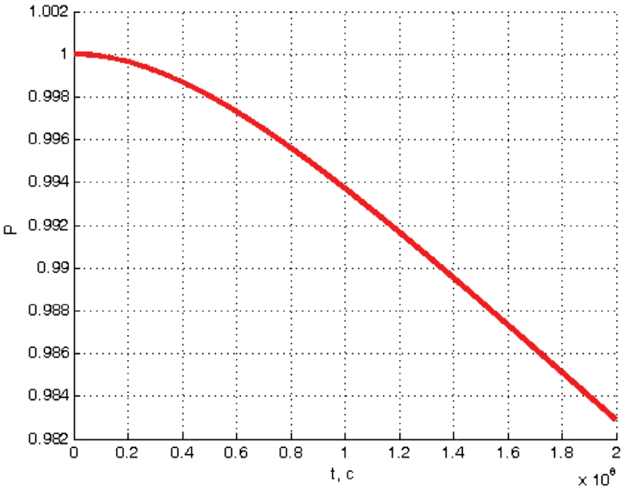



Figure 2. Probability of no-failure of CNE (hot standby) in adverse conditions for three additional countermeasures modules

Second variant. The model of CNE function-level fault-tolerance has the form of a cold standby system with three additional countermeasures modules (relative to the general use CNE). In such systems, at any time only one module is on and ensuring countermeasures against adverse conditions. If one of the modules fails under ITI, the next countermeasures module becomes active.

Assuming that for each countermeasures module the failure rate is constant and equals to λ, let us write the probability of no-failure of CNE (cold standby) in adverse conditions for three additional countermeasures modules using [5] as:

$$P_{CNE}^{CSB}(t) = e^{-t\lambda}\left(1 + \frac{\lambda}{\lambda_{\Pi}}(1 - e^{-t\lambda})\right) + \\ + e^{-t\lambda}\left(\frac{\lambda}{\lambda_{\Pi}}\right)^2 (1 - e^{-t\lambda_{\Pi}} - \lambda_{\Pi} t e^{-t\lambda_{\Pi}}), \quad (4)$$

where $\lambda_{\Pi}$ is the failure rate of the CNE switch (set of hardware and software) that activates the countermeasures modules depending on the presence of adverse conditions.

Figure 3 shows the probability of no-failure of CNE (cold standby) in adverse conditions for three additional countermeasures modules under the following initial conditions: $\lambda = 1{,}0{\cdot}10^{-8}$, $\lambda_{\Pi 1} = 1{,}0{\cdot}10^{-7}$, $\lambda_{\Pi 2} = 1{,}0{\cdot}10^{-8}$, $\lambda_{\Pi 3} = 1{,}0{\cdot}10^{-2}$.

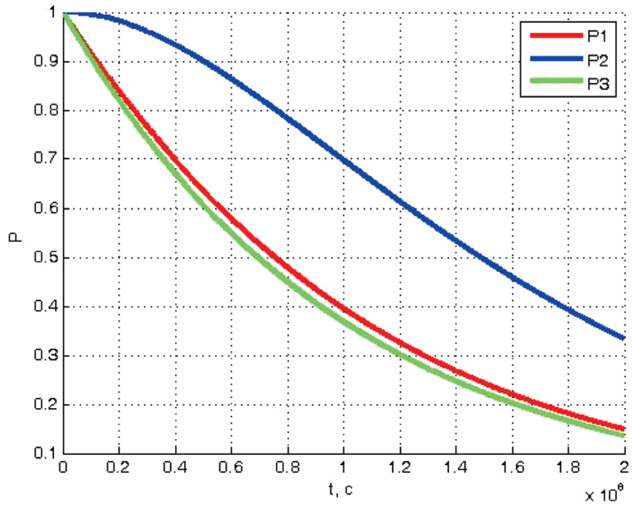



Figure 3. Probability of no-failure of CNE (cold standby) in adverse conditions for three additional countermeasures modules

In the simplest case, using [5], let us define the probability of CNE recovery in adverse conditions, assuming that the repair rate is constant and equals to μ, has an exponential distribution, as follows:

$$P_{CNE}^{REC}(t_R) = 1 - e^{-t_R \mu}, \quad (5)$$

where $t_R$ is the CNE recovery time.

For the quantitative evaluation of the interdependent CNE failure and recovery processes in adverse conditions it is suggested to use the CNE availability coefficient that is defined as the probability of CNE performing the functions defined for the consumer and according to the specified parameters at a given moment in time and in adverse conditions. The following formula can be conveniently used for calculation of the CNE availability coefficient in adverse conditions:

$$P_{ACNE}(t_{NO}) = \frac{\mu}{\mu + \lambda} + \frac{\lambda}{\mu + \lambda} e^{-(\mu+\lambda)t_{NO}}, \quad (6)$$

where $t_{NO}$ is the CNE non-operability time.

Diagram and formula for evaluation of allowable risk of CNE function-level fault tolerance.

For the expert analytical evaluation of the CNE function-level fault tolerance in adverse conditions let us define the allowable risk level of its violation according to the ALARP principle [4], i.e. risk "as low as reasonably practicable", with the use of the diagram in Figure 4 and Table 2.

The ALARP area of violation of CNE function-level fault tolerance in adverse conditions corresponds to the navigation signals parameter values that are within their tolerances. The allowable value of risk of CNE function-level fault tolerance violation according to the ALARP principle (the upper part of the ALARP region) is only ensured if the navigation signal parameters are within the specified tolerances.

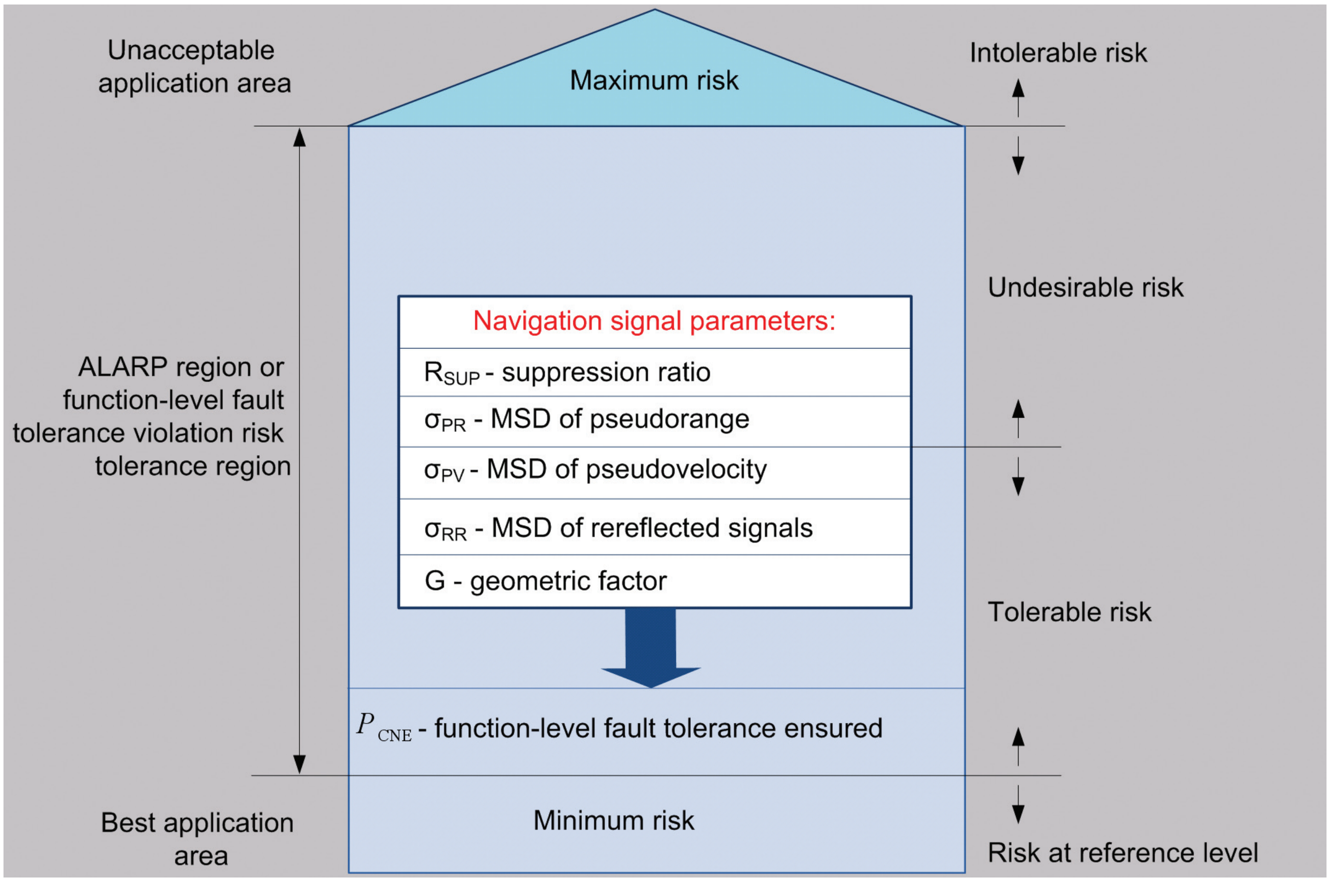



Figure 4. Diagram of allowable risk of CNE function-level fault tolerance level violation according to the ALARP principle

It is proposed to identify the risk of navigation signal parameter distortion in generic CNE hardware and software by means of monitoring the following parameter values:

- power of man-made interference, suppression ration not more than 30 dB,
- pseudorange of navigation signals, mean square deviation (MSD) of the pseudorange must not exceed 5 meters,
- navigation signal pseudovelocity, MSD must not exceed 0.01 m/s,
- multipath effect (navigation signal reflection from urban structures and terrain features), MSD of positioning not more than 10 meters, geometric factor not worse that 15 (minimization of the navigation signal rereflections accepted for processing).

According to Table 2, the CNE failure frequency ($10^{-8}$ 1/h) and low risk level will correspond with the allowable value of the probability of no-failure $P_{CNE} \geq 0.8$ and minimal value of the harm of non-provision of quality navigation services to the consumer.

We deduce the value of allowable risk of CNE function-level fault tolerance level violation using the following formula:

$$R_{ALW} = \sum_{i=1}^{n}((1-P_{CNE,i})\gamma_j), \qquad (7)$$

where $P_{CNE,i}$ is the probability of no-failure of CNE with the $i^{th}$ CNE ITI countermeasures module, $\gamma_j$ is the value of harm of the $j^{th}$ level.

## Conclusion

The article proposes a model that allows representing the processes of navigation signal provision to consumers in the form of a conventional state graph. The model includes mathematical expressions for quantitative evaluation of the probability of no-failure for hot and cold standby systems with three modules of information technology interference countermeasures, probability of recovery identification and

**Table 2. Evaluation of allowable risk of CNE function-level fault-tolerance violation**

| Risk level | Frequency of failures | Evaluation of function-level fault tolerance level | Value of damage caused by CNE failure (points) |
|---|---|---|---|
| Low | $10^{-8}$ 1/h | Tolerable $P_{CNE} \geq 0{,}8$ | $\gamma_L$=1÷2 |
| Medium | $10^{-5}$ 1/h | Acceptable $0{,}6 \leq P_{CNE} \leq 0{,}7$ | $\gamma_M$=3÷4 |
| High | $10^{-3}$ 1/h | Intolerable $0{,}5 \leq P_{CNE} \leq 0{,}6$ | $\gamma_H$=5÷10 |

CNE availability coefficient, as well as the allowable risk of CNE fault tolerance violation.

## References

1. Federal Target Program Support, Development and Use of GLONASS for the period between 2012 and 2020, <http://www.gost.ru>.

2. Boeing and QinetiQ working on a highly autonomous military UAV: the high-altitude drone is to operate without landing not less than five years with a 500-kg (1000 lbs) payload, <http://www.roscosmos.ru>.

3. Yatsenkov VS. Osnoivy sputnikovoy navigatsii. Sistemy GPS NAVSTAR i GLONASS [Introduction to satellite navigation. GPS NAVSTAR and GLONASS systems]. Moscow: Goriachaia linia-Telekom; 2005 [in Russian].

4. Shubinsky IB. Nadiozhnie otkazoustoychivie informatsionnie systemi. Metodi sinteza [Dependable failsafe information systems. Synthesis methods]. Ulianovsk: Oblastnaya tipografia Pechatny dvor; 2016 [in Russian].

5. Kapur K, Lamberson L. Reliability in engineering design. Moscow: Mir; 1980.

6. Babich OA. Obrabotka informatsii v navigatsionnykh kompleksakh [Information processing in navigation systems]. Moscow: Mashinostroenie; 1991 [in Russian].

## About the authors

**Sergey M. Klimov**, Doctor of Engineering, Professor, Head of Division, 4th Central Research and Design Institute of the Ministry of Defense of Russia. 12 B. Komitetskaya Str., app. 105, 141092, Moscow Oblast, Korolyov, mkr. Yubileyny, Russia, phone: +7 (985) 928 13 55, e-mail: klimov.serg2012@yandex.ru

**Aleksey Yu. Polovnikov**, Candidate of Engineering, Associate Professor, Chief Researcher of Division , 4th Central Research and Design Institute of the Ministry of Defense of Russia. 9/18 Mayakovskogo Str., app. 70, 141090, Russia, Moscow Oblast, Korolyov, mkr. Yubileyny, phone: +7 (985) 119 24 65, e-mail: plv71@yandex.ru

**Aleksey P. Sergeev**, Senior Researcher, 4th Central Research and Design Institute of the Ministry of Defence of Russia. 27 Lenina Str., app. 159, 141070, Russia, Moscow Oblast, Korolyov, phone: +7 (926) 493 51 16, e-mail: lex_serg@mail.ru

**Received on 28.03.2017**

Original article
DOI: 10.21683/1729-2646-2017-17-2-48-55

# Methods of traction rolling stock fire safety analysis

**Olga B. Pronevich,** *JSC NIIAS, Moscow, Russia, e-mail: O.Pronevich@vniias.ru*

*Olga B. Pronevich*

**Abstract. Aim.** *Fire safety of a protection asset is the state of a protection asset that is characterized by the capability to prevent the occurrence and development of fire, as well as the effects of hazardous factors of fire on people and property [1]. The traction rolling stock (TRS) is one of the primary protection assets on railway transport. Managing TRS fire safety involves a large volume of information on various TRS types: possible fire-hazardous conditions, fire safety systems, parameters of TRS-related processes. That means that efficient management must be built upon analysis that allows identifying trends and factors of fire hazard development. The analysis should be organized in such a way as to allow its results to be used in evaluation of composite safety indicators [2]. The required applied nature of such analysis is also obvious. Given the above, it should be noted that the applied research indirectly solves the task of using the results of fundamental research to address not only cognitive, but also societal issues [3]. The aim of this article is to structure the most efficient applied and theoretic methods of analysis and to develop a structure for systems analysis of TRS fire safety.* **Methods.** *The multitude of factors that affect the condition of TRS can be divided into two groups: qualitative and quantitative. Importantly, it is impossible to completely research the impact of all the elements of a complex technical system that is TRS on fire safety. We have to examine a part of the whole, i.e. a sample, and then use probabilistic and statistical methods to extrapolate the findings of sample examination to the whole [4]. An analysis of a data set requires a correctly defined sample. At this stage, the quality of information is the most important criterion. The list of raw data was defined based on the completeness of the description, reliability of the sources. Then, in a certain sequence, the data was analyzed by means of qualitative and semi-quantitative methods. First, given the impossibility to establish evident connections (destroyed by the hazardous effects of fire) between the condition of units that preceded the fire, the Pareto analysis was used. The research involved root cause analysis (Ishikawa diagram). Subsequently, cluster analysis of fire-hazardous situations was used. The main purpose of cluster analysis consists in establishing generic sequences of events that entail TRS fires. For that purpose, a description of possible fire-hazardous states of traction rolling stock is required, i.e. a multitude of events and states must be described. Dependability analysis can be successfully performed by representing the safety state information in terms of the theory of sets [5]. The sets of hazardous fire-related TRS events are represented in the form of partially ordered sets. Processing of such sets that are non-numeric in their nature cannot be performed by means of statistical procedures based on addition of parametric data. For that reason the research used mathematical tools based on the notion of type of distance. A part of data that have quantitative characteristics was analyzed statistically.* **Results.** *The TRS fire safety data analysis methods presented in this article that include methods of numeric and non-numeric data processing allowed developing a formatted list of fire hazard factors that enable the creation of a practical method of TRS fire risk calculation. An algorithm is proposed for application of qualitative and quantitative methods of analysis of data of various numerical natures. An example is given of the algorithm's application in the analysis of diesel engine fire safety. The proposed method can be used for analyzing anthropogenic safety in terms of listing the factors involved in risk assessment.*

**For citation:** *Pronevich OB. Methods of traction rolling stock fire safety analysis. Dependability 2017;2: 48-55. DOI: 10.21683/1729-2646-2017-17-2-48-55*

## Introduction

Any statistical research starts with the description of the data type and structure. In the case of fire safety analysis, the statistical data represent the value of a property of traction rolling stock (TRS) that contributes to the possibility of initiation and propagation of fire. The values can be quantitative or qualitative. If measurement is made using several quantitative or qualitative properties, the resulting statistical data in the facility is a vector [6]. However, vector calculus involves using cumbersome mathematical tools, as well as developing a coordinate system and defining the list of operations that could be used in processing of heterogeneous data. Due to the applied nature of this research it is advisable to decompose the task to the analysis of one-dimensional observable values, define one-dimensional statistical research methods, the sequential use of which will provide as much information on the object as a multi-dimensional analysis would. Based on the type of raw data all available methods of analysis are divided into two parts: numerical statistics and statistics of non-numerical objects. The latter is crucial for two reasons. First, a significant proportion of the information on cases of TRS fires comes from reports of fire and reports on immediate (technical) causes of fire that are forms with open questions. These documents contain information in numerical and non-numerical form. The second reason is the nature of the assessment of the engine condition's contribution to the probability of fire. The main source of such information is the expert's opinion that is usually expressed in non-numerical form.

The approach suggested in this article aims to deliver a list of fire hazard factors that fall into the categories of numerical and non-numerical objects and make most complete information required for the construction of a fire risk assessment model.

## Selection of methods of acquisition and analysis of traction rolling stock fire safety data

A researcher involved in processing of traction rolling stock fire safety data has two sources of information at his/her disposal. The first one is the results of observation of TRS fire cases that produce information in the form of data sample retrieved from a population. The size of such

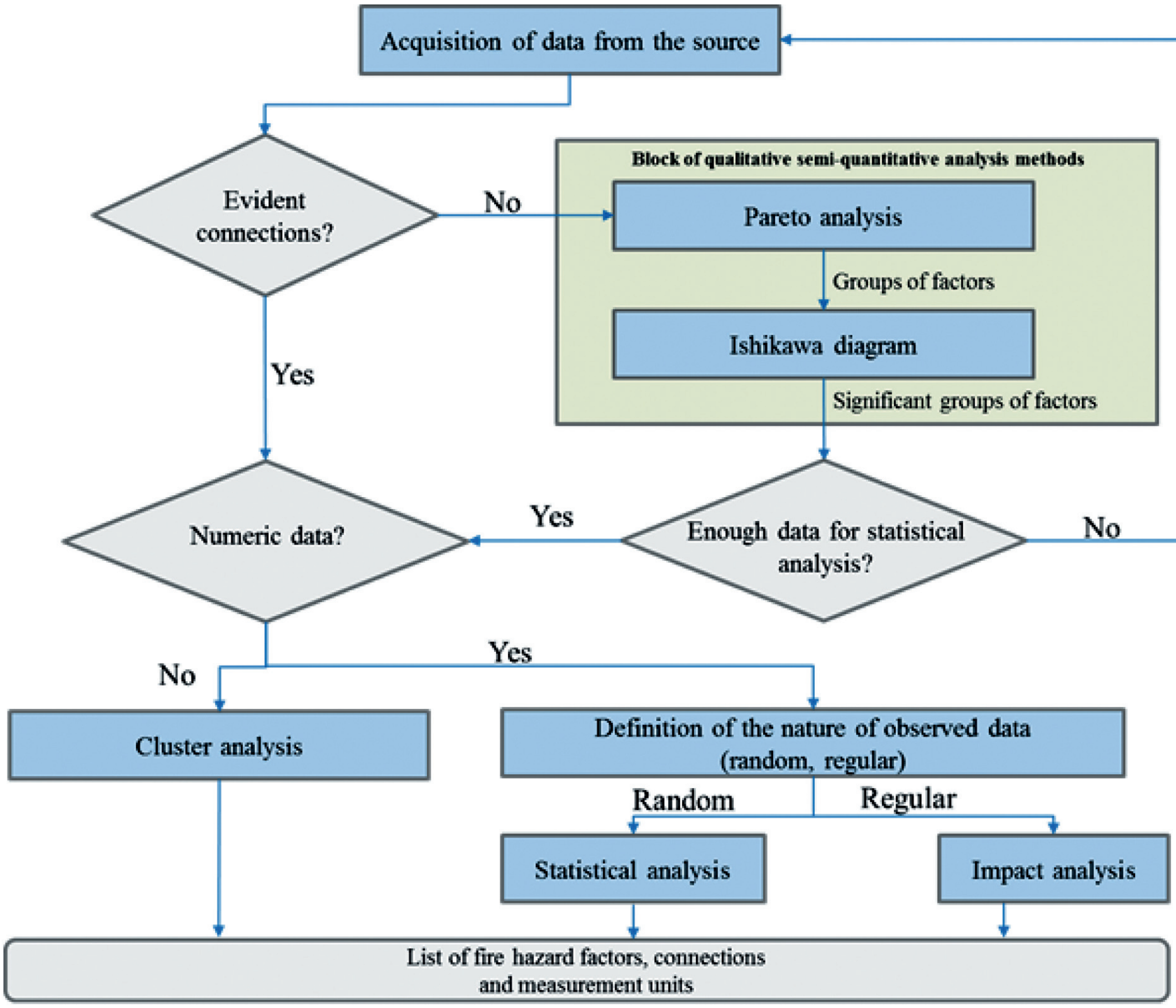



Figure 1. Algorithm of data analysis method selection

**Table 1. Analysis and classification of methods of data acquisition of traction rolling stock fire safety**

| Type of source | Source | Method of data acquisition |
|---|---|---|
| Documental | Internal investigation report | Manual analysis: arrangement of data, classification of data |
| | Report on the immediate (technical) cause of fire | |
| | Report of inspection of traction rolling stock after fire | |
| | Engine technical condition log | Manual analysis: logical analysis, data classification, expert analysis |
| | Automated system for fire safety management | Data grouping, initial statistical analysis |
| Expert group | Analysis of JSC RZD facilities and rolling stock fire safety | Manual analysis: data integration and classification |
| Experiment | (observation under altered conditions) | Manual analysis: data registration, logical analysis and classification |

samples is restricted by two factors: the observation period and the number of observed properties. The number of observed properties over the entire observation period (2011 – 2015) was not stable due to the changes in the data recording and storage procedure. The second source is the a priori information on the TRS design and possible violations of maintenance and operation procedures that cause fire-hazardous situations collected by the time the analysis started. Unlike the observed properties, this data is structured. Thus, when working with information sources, the primary task was to retrieve data, i.e. structuring data from non-structured or semi-structured documents. Table 1 provided the classification of fire safety information sources and methods of data acquisition from the sources for subsequent analysis.

The sampling is done at the stage of initial data processing. The result of data retrieval from the source is partially ordered numerical and non-numerical information. This information differs in the level of structuring, homogeneity and most importantly data interconnection. The algorithm shown in Figure 1 was developed for the purpose of analyzing such data.

## Qualitative and semi-quantitative methods of traction rolling stock fire safety analysis

As the result of data retrieval from the source and grouping of data on the number and causes of fires it was established that out of 334 fires of diesel and electric engines over the considered period 201 fires occurred due to the fault of motive power maintenance depots (MPMD), 31 due to the fault of service enterprises, 35 due to the fault of motive power operation depots (MTOD), 15 due to the fault of locomotive repair shops, 5 through the fault of other third parties.

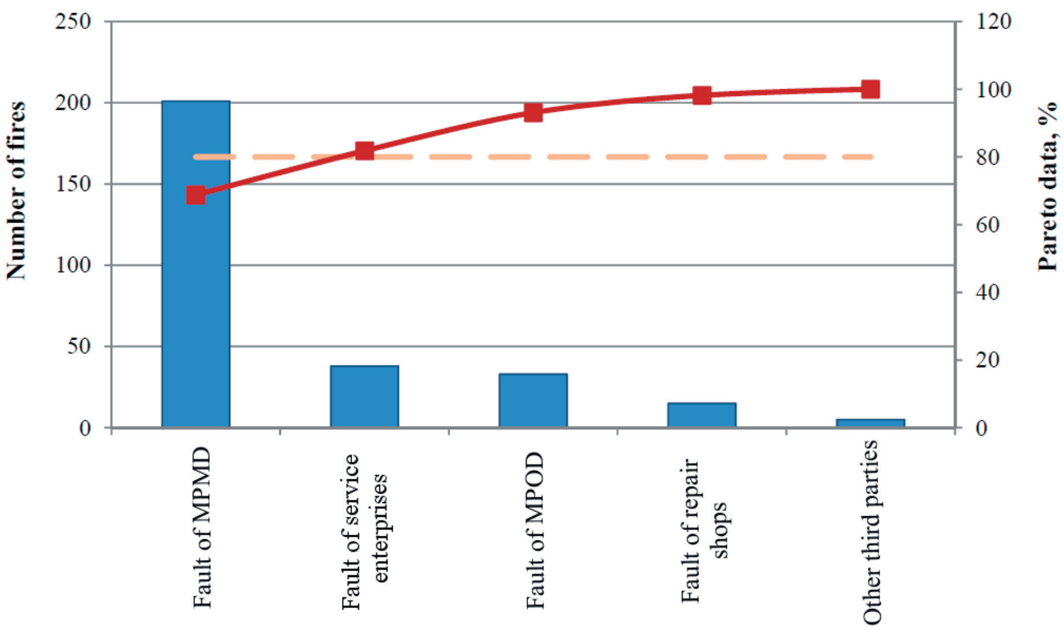



Figure 2. Pareto diagram of those guilty of diesel and electric engine fires for the record period

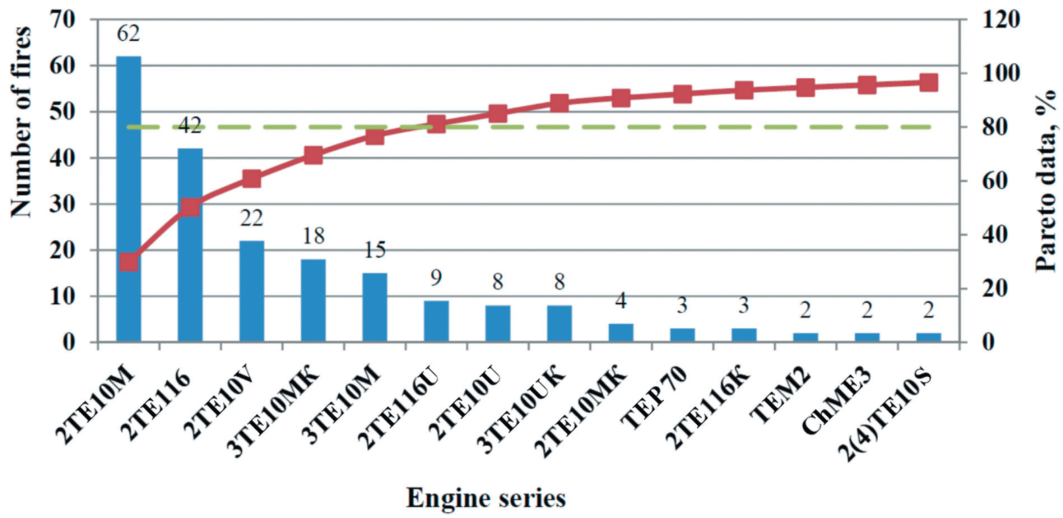



Figure 3. Number of fires between 2011 and 2015 per series of engines

It should be noted that most service enterprises that currently are not part of JSC RZD used to be motive power maintenance depots. Despite the reorganization and incorporation of a part of MPMDs as limited liability companies that are not part of the JSC RZD corporate structure the problem of fires caused by MPMDs and service enterprises still remains. Only the percentages changed. If between 2011 and 2013 the number of fires due to the fault of MPMD amounted to 80 percent, due to the fault of service enterprises to 4 percent, then in 2014 the MPMDs and service enterprises shared the guilt 46 to 41 percent respectively, i.e. 80 percent of fires over 4 years were due to the poor quality of maintenance. The Pareto analysis of the parties guilty of fires is given in Figure 2.

The Pareto diagram allows concluding that the main cause of TRS fires is the poor quality of technical inspections and maintenance. That means that further analysis

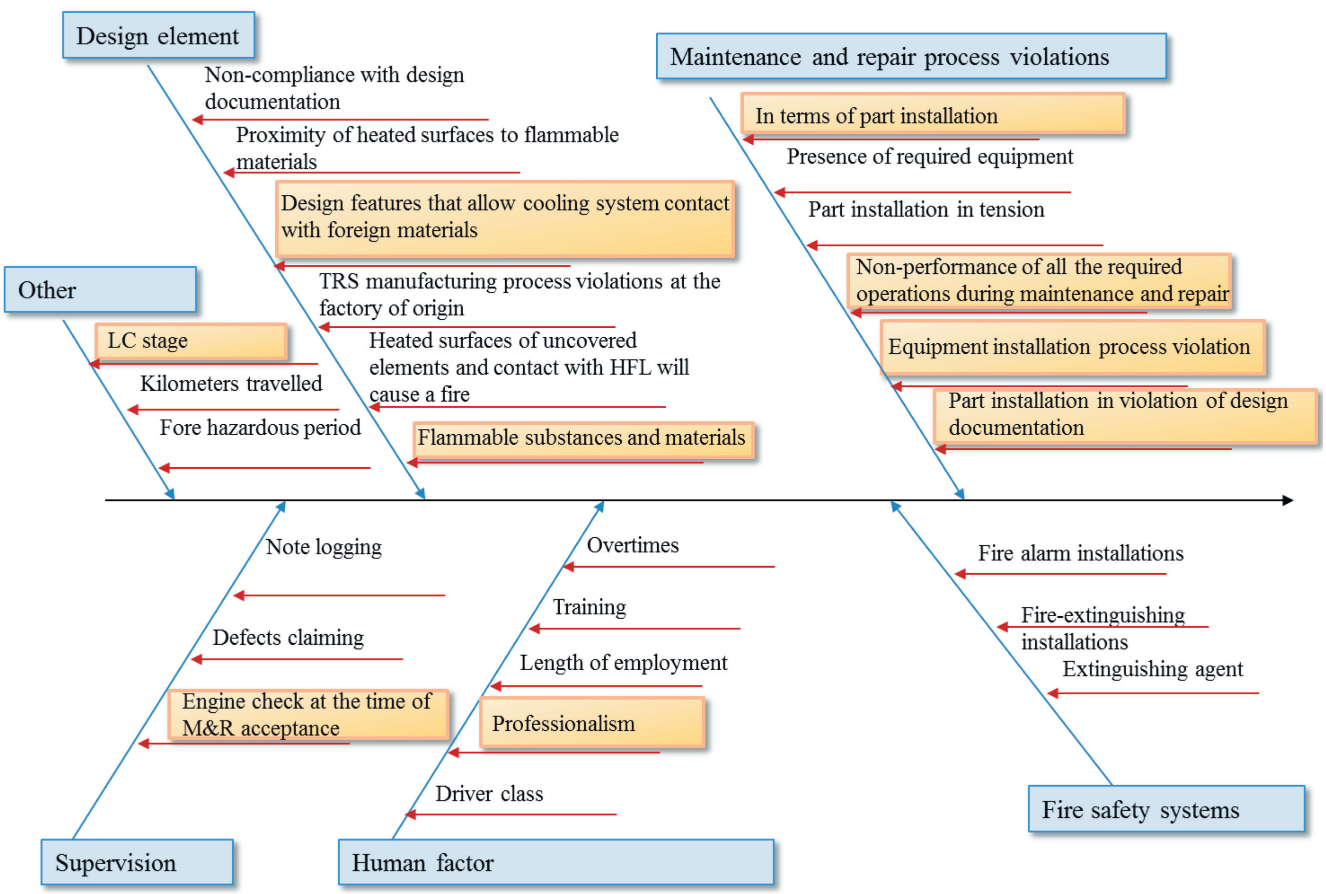



Figure 4. Cause-and-effect relationships between diesel and electric engine fires and the contributing factors

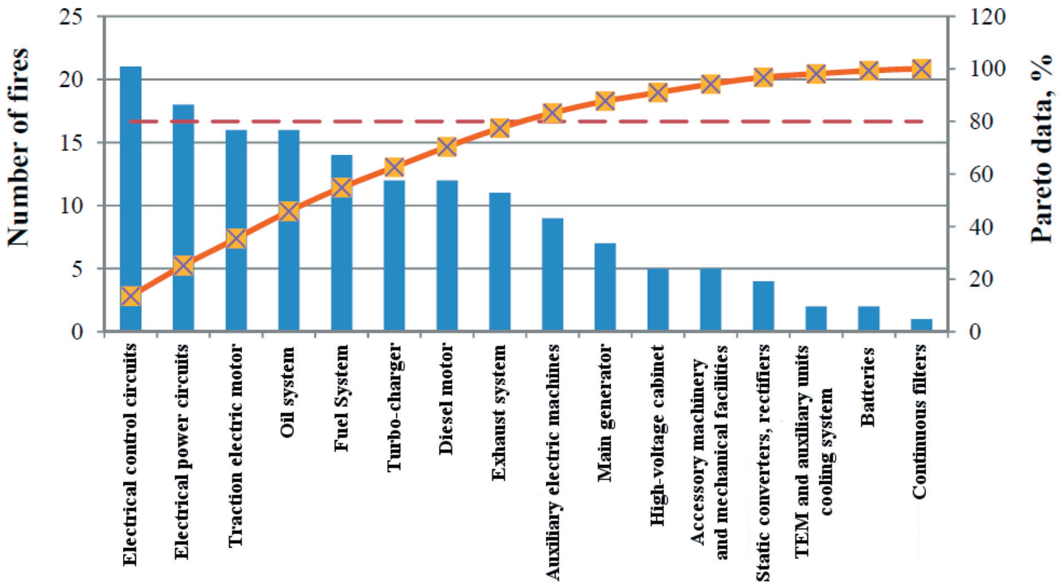



Figure 5. Number of fires per fire-hazardous engine components

should concentrate on detailing and structuring of the data on specific engine conditions that entail fires or the actions of the employees involved in their operation and maintenance. However, before proceeding to such analysis it is important to take into consideration the design differences of the engines of various series. Figure 3 shows the number of fires over the considered period per engine series. As we can see in Figure 3, 37.6 percent of all fires over the considered period is attributed to the 2(3)TE10M series engines, 19 percent to the 2(3)TE10MK series engines, 12.4 percent to 2(3) TE10V series engines, 10.1 percent to the 2(3)TE10MK series engines. That can be explained by the fact that most (63 percent) locomotives operated throughout the JSC RZD network belong to the 2TE10 and 2TE116 series. Those are the most commonly operated engines, which also contributes to the high fire statistics figures for those series. The remaining 37 percent of the operated diesel engine fleet of the JSC RZD network belong to the series, for which statistical data is not available or fires are rare.

Out of the Pareto diagram shown in Figure 3 it can be concluded that most fires are associated with the 2TE10M, 2TE116, 2TE10V, 3TE10MK series of diesel engines. A research of fire analysis materials allowed establishing cause-and-effect relationships between fires and technical malfunctions. Figure 4 shows the Ishikawa diagram of the cause-and-effect relationship between engine fires and the contributing factors. According to the Ishikawa diagram construction rules, the factors that contribute to a problem are shown with arrows that deflect to the right from the main arrow, while those that neutralize the problem are shown with arrows that deflect to the left. The neutralizing factors include the elements of the fire safety system (FSS): fire alarm installations (FAI), fire-extinguishing installations (FEI), extinguishing agents (EA). Thus, we can see that the occurrence of fire in traction rolling stock can be contributed by both individual indicators, and sets of indicators of various factors. The Ishikawa diagram (Figure 4) highlights the indicators of factors that in most cases caused fires in the engines of the 2TE10M, 2TE116, 2TE10B and 3TE10MK series.

As in most cases fires affect engines of specific series, let us examine which units and components of such engines are the most fire-hazardous. Figure 5 shows the analysis of fires in the engines of the 2TE10M, 2TE116, 2TE10B and 3TE10MK series over the considered time period per units and components affected by fire.

The Pareto diagram in Figure 5 shows that the bulk of the fire hazard (80 percent) for these series of engines is associated with the following set of units: electrical control circuits, electrical power circuits, traction electric motor, oil system, fuel system, turbo-charger, diesel motor, exhaust system, auxiliary electric machine. I.e. at this stage of analysis one may talk about the development of a sample of fire-hazardous units, of which the fire hazard evaluation will characterize the main body of TRS fire safety in general.

Each of the fire-hazardous units has a set of components that initiate fire. Thus, for example, in the case of electrical circuits that is the insulation and the cores. For the traction electrical motors the list is longer, from the armature to the feeder cables. Fire initiation conditions are also associated with fire-hazardous events that cause fire in a unit's component. Let us examine them in detail. The research of diesel engine fires investigation materials shows that the most frequent event is a short circuit that produces sparks with subsequent inflammation of cable cores and wires. The list of fire-hazardous events for diesel engines is as follows: electrical arc, sparks, short circuit sparks due to short-circuiting of wires, to frame, short circuit sparks due to turn-to-turn short circuit, flashover, burning of flammable materials, heating, incandescent gas, etc. As the described diesel engine characteristics that affect its fire safety are not numeric, according to the algorithm of data analysis method selection (Figure 1) further analysis of such data should be based on the cluster method.

## Cluster analysis of non-numeric statistical data

Based on the investigation materials and data from automated fire safety systems, classifiers of fire-hazardous events and fire-hazardous units were developed. As the result of fire data analysis, using the events and units classifiers, chains of fire-hazardous events were constructed. Each of them corresponded to specific units.

Further analysis covers the construction of generic chains of events. A chain of events is understood as a sequence of finite or enumerable infinite number of events, of which the characteristic property is that, non-strictly speaking, the condition that occurs before or after TRS operation corresponds to a specific set of parameters that do not depend on the engine's condition before the event chaining.

*The object of analysis* is the chain of events, a partially ordered set. *The aim of analysis* is to develop the search rules for common features in the chains of events and construction of chains with the common feature of generic event scenarios. Achieving that goal will involve the evaluation of the proximity of chains of events by means of cluster analysis.

Let us formalize a number of concepts:

$Z$, a partially ordered set of all chains of events.

$A_i$, a partially ordered subset (POS) of the $Z$ set of $i^{th}$ type.

$B_j$, POS of the set $Z$.

Each subset $B_j$ can be replaced with a universal set that characterizes the $i^{th}$ type set ($A_i$ subset).

The distance between two subsets $B_k$ and $B_l$, that characterizes the proximity of the subsets, is calculated using the formula (1.1):

$$d_{lk} = \sum_{i=1}^{5} r_i \qquad (1.1)$$

Where

$$r_i = \begin{cases} 0, x_{ki} = x_{li} \\ 1, x_{ki} \neq x_{li} \end{cases}$$

$x_{ki}$ is an event at the $i^{th}$ position in subset $B_k$;

$x_{li}$ is an event at the $i^{th}$ position in subset $B_l$.

By combining the subsets $B_j$ based on feature $d_{lk}$ we obtain a cluster. Table 2 shows the correspondence between the value of feature $d_{lk}$ and commonality level.

**Table 2. Spacing of subsets and level of commonality**

| | ***d*** | | | | |
|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** |
| Level of commonality | High | Significant | Insignificant | Low | No |

When clustering standard event scenarios, subsets with commonality levels «high» and «significant» were chosen.

The result of event clustering is shown in Table 3. Cluster power is the number of constituent and common chains of events. FHE is a fire-hazardous event.

Similarly, the generic unit groups were defined. In order to construct generic fire scenarios for diesel engines, a correspondence analysis of generic unit groups and fires from the event cluster was performed. If fires from the generic unit groups correspond with the fires from the event cluster, scenarios can be built. Frequent scenarios are built if at least 4 fires correspond. The number of corresponding fires is

**Table 3. Example of clustered events**

| Cluster no. | Power | Years/ months | | FHE1 | FHE2 | FHE3 | FHE4 | FHE5 |
|---|---|---|---|---|---|---|---|---|
| 1 | 8 | October 2014 | Cluster center | *Destruction, rupture* | *Sparking* | *Spark hits* | *0* | *Spark* |
| | | March 2013 | Cluster elements | Absence (of a part) | Sparking | Spark hits | 0 | Spark |
| | | May 2013 | | Damage | Sparking | Spark hits | 0 | Spark |
| | | April 2014 | | Use of nonstandard parts | Sparking | Spark hits | 0 | Spark |
| | | May 2013 | | Use of nonstandard parts | Sparking | Spark hits | Spark hits | Spark |
| | | March 2014 | | Defect | Sparking | Spark hits | 0 | Spark |
| | | April 2014 | | Damage | Sparking | Spark hits | 0 | Spark |
| | | July 2013 | | Destruction, rupture | Sparking | Spark hits | 0 | Spark |

**Table 4. Built scenarios of diesel engine fires with the power level of 5.**

| Scenario | Units | Events | | | | Power |
|---|---|---|---|---|---|---|
| 1 | Diesel motor exhaust | Absence (of a part) | Damage | Use of nonstandard parts | Destruction, rupture | 4 |
| | Cooling system | Sparking | Spark hits | | | |
| 2 | Fuel system | Absence (of a part) | Incorrect installation | Damage/wear (ageing) | Rupture | 4 |
| | Exhaust system, draining system | Heating of flammable materials and substances, their contact with hot parts of the engine | | | | |
| 3 | Electrical systems | Insulation disruption/ chaffing, rupture | Short-circuiting of cables | Short circuit to frame | Heating | 8 |

the power of the scenario. Table 4 shows examples of built scenarios of diesel engine fires.

The analysis of non-numeric data results in fire scenarios that include the units and series of events that entail fires. Fire risk evaluation based on actual condition of TRS must take into consideration those conditions that contribute to the probability of hazardous fire scenarios.

## Definition of the nature of observed data

The numeric characteristics of fire TRS safety include the number of fires within the 2011 – 2015 observation period. The observation interval is one month. Before submitting the observation results to statistical processing it must be made sure that they make a truly random sample, i.e. are stochastically independent (alternatively, the observation result may be dependent on the order number, observation time, presence of cyclic or monotonous bias) [7]. For that purpose let us analyze the set of sample data using the criterion of "run up" and "run down". This criterion was chosen because of the ability to "grasp" the drift (along the sample observation) of the mean value in the periodic distribution under study. The initial sequence (number of fires per month) is associated with a sequence of pluses and minuses. At the $i^{th}$ position in the sequence is a plus if $x_{i+1} - x_i > 0$, a minus if $x_{i+1} - x_i < 0$. If two or more consecutive observations are equal, only one of them is taken into consideration, the others are excluded from the sequence. The series criterion is based on the affirmation: if the sample is random, in the character sequence it forms the total number of series ($v(n)$) cannot be too small, while their length ($t(n)$) cannot be too large. In the quantitative form this rule is as follows:

$$v(n) > [\frac{1}{3}(2n-1) - U(\alpha)\sqrt{\frac{16n-29}{90}}$$

$$t(n) < t_0(n)$$

Value $t_0(n)$ depending on the length of sequence ($n$) is defined as follows: if $n \le 26$, $t_0(n) = 5$; if $26 < n \le 153$, $t_0(n) = 6$; if $153 < n \le 1170$, $t_0(n) = 7$.

The analysis of time sequence of fires has shown that the sequence of the number of fires is a random sample. That means that further analysis should be made by means of applied statistics. Among other things, fire forecasting must involve the evaluation of the lower and upper limits of this probability. In [8], a detailed account is given of the special aspects of estimating the probability of fire occurrence on diesel engines of various types. They therefore will not be scrutinized in this article. The results of assessment of the probability of fire are used as a key factor in the construction of the risk assessment model.

## Conclusion

The article highlights the requirement for the development of an algorithm for selection of an analysis method of raw data on a facility subject to several sources of information. The author defines the primary methods of analysis subject to the presence of numeric and non-numeric data. She demonstrates the sequential application of qualitative and semi-quantitative data analysis methods without evident connections with grouping and classification of the end results. Cluster analysis of non-numeric statistics is used for construction of generic fire scenarios.

The systems approach to the application of various types of analysis allows defining a list of TRS parameters to be taken into consideration in risk assessment, defining the measurement scale and the nature of observed values.

## References

1. Federal Law No. 123-FZ Technical regulations on fire safety requirements dated 22.07.2008.

2. Shubinsky IB, Zamyshliaev AM, Pronevich OB. Graph method for evaluation of process safety in railway facilities. Dependability 2017;1:40-45 [in Russian].

3. Gertsog GA. Osnovy nauchnogo issledovania: metodologia, metodika, praktika: ouchebnoie posobie [Foundations of scientific research: methodology, methods, practice: a study guide]. Chelyabinsk: Chelyabinsk State Pedagogical University Publishing; 2013 [in Russian].

4. Orlov AI. Organizatsionno-ekonomicheskoie modelirovanie. Chast 3. Statisticheskie metody analiza dannych [Business modelling. Part 3. Statistical methods of data analysis]. Moscow: Bauman MSTU Publishing; 2012 [in Russian].

5. Shubinsky IB. Nadiozhnie otkazoustoychivie informatsionnie systemi. Metodi sinteza [Dependable failsafe information systems. Synthesis methods]. Moscow: Dependability; 2016 [in Russian].

6. Orlov AI. Ekonometrika; ouchebnik dlia vuzov. Izd. 4-e, dopoln. i pererab [Econometrics: a college textbook. 4th edition, revised and enlarged]. Rostov-on-Don: Feniks; 2009 [in Russian].

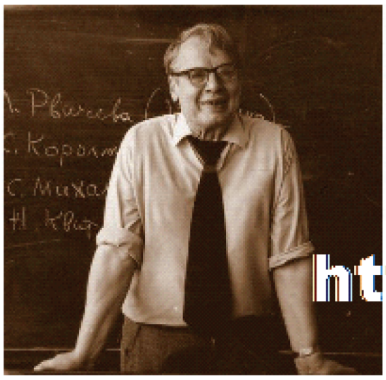
7. Aivazian SA, Yeniukov IS, Meshalkin LD. Prikladnaia statistika: Osnovy modelirovania i pervichnaya obrabotka dannykh. Spravochnoie izdanie [Applied statistics: Introduction to modelling and initial data processing. Reference guide]. Moscow: Financy i statistika; 1983 [in Russian].

8. Shubinsky IB, Pronevich OB, Danilova AD. Osobennosti otsenki veroiatnosti vozniknovenia pozharov na teplovozakh razlichnykh seriy [Special aspects of estimating the probability of fire occurrence on diesel locomotives of various types]. Dependability 2016;4:24-29 [in Russian].

## About the author

**Olga B. Pronevich,** Head of Unit, JSC NIIAS, Moscow, Russia, tel.: +7 (495) 967 77 05, ext. 516, e-mail: O.Pronevich@vniias.ru

**Received on 17.04.2017**




**http://Gnedenko-Forum.org/**

**Dear colleagues!**

In 2005 the informal Association of Experts in Reliability, Applied Probability and Statistics (I.G.O.R.) was established with its own Internet website GNEDENKO FORUM. The site has been named after the outstanding mathematician Boris Vladimirovich Gnedenko (1912-1995). The Forum's purpose is an improvement of personal and professional contacts between experts in the mathematical statistics, probability theory and their important branches, such as reliability theory and quality control, the theory of mass service, storekeeping theory, etc.

Since January 2006, the Forum has published a quarterly international electronic magazine

***"Reliability: Theory and Applications".***

The magazine is registered with the Library of Congress in the USA (ISSN 1932-2321). All rights reserved for authors so that articles can be freely published in any other publications or presented at conferences.


**Join Gnedenko Forum!**

**Welcome!**

**More than 500 experts from 44 countries worldwide have already joined us!**

To join the Forum, send a photo and a short CV to the following address:

***Alexander Bochkov, PhD***
**a.bochkov@gmail.com**

**Membership is free.**

# REQUIREMENTS OF EDITION ON EXECUTION OF PAPERS IN JOURNALS OF PUBLISHING GROUP OF IDT PUBLISHERS

A letter from the organisation where the author (s) works or from the author (s) personally with the paper offered for publication should be sent to the de facto editorial office address: 107078, Moscow, 5 Orlikov lane, Office 755, LLC "JOURNAL DEPENDABILITY" or e-mail: E.Patrikeeva@gismps.ru (in scanned form). The letter should be attached to a paper text containing the summary and keywords, information on authors, bibliographic list, and one complete set of figures. All listed items are to be presented in an electronic form (on CD or via the e-mail address provided above).

**Attention!** Titles of papers, names of authors, summary and keywords must be presented, in Russian and English languages, according to the requirements of the Higher Attestation Commission. The information on each author should contain the following standard data:

- Surname, name, patronymic;
- Scientific degree, academic status, honorary title;
- Membership of relevant public unions, etc.;
- Place of employment, position;
- The list and numbers of Journals of IDT Publishers in which papers of the author have been previously published;
- Contact information.

Texts should be presented in Word 97-2003 format in a 12-point typeface; the text should not be formatted. Paragraphs should be arranged by pressing the "return" key. The text of the paper should be double-spaced on pages of A4; on the left there should be a margin of 2 cm; pages should be numbered, the «first line indent» is obligatory.

All alphabetical designations represented in figures should be explained in the body text or in a legend. Inconsistencies between designations in figures and in the text are inadmissible. Numbering should only be applied to those formulas and equations that are referred to in the text.

Simple formulas appearing directly in the text (for example, $m^2$, $n^2t$, $c = 1 + DDF – A_2$), and the Greek letters and symbols, for example, β, © may be typed using the Symbol font. When it is not possible to type directly in the text editor, use the "Microsoft Equation" formula editor (available with the complete installation of Microsoft Office) or the "Mathtype" formula-editing program. Representation of formulae in the text in the form of images is not admissible. Photos and figures for papers should be provided in individual files with extension TIF, EPS or JPG with a resolution of not less than 300 dpi. The list of literature referred to in the paper (bibliography) is presented according to order of citation and provided at the end of paper. References to the literature in the text are marked by serial numerals in square brackets.

**To authors that are published in journals of "IDT Publishers".**

In addition to the journal, information on each author will be presented at the techizdat.ru site in the «Authors» section on the individual web page.

Authors of papers for publication have the opportunity to send an electronic photo and additional material to appear on this individualised Internet-business card. At their own discretion, authors can present more details about themselves, interesting examples and stories of solutions to technical problems, about contemporary problems according to subjects of corresponding journal, etc. This material should not exceed 1000 characters including spaces.

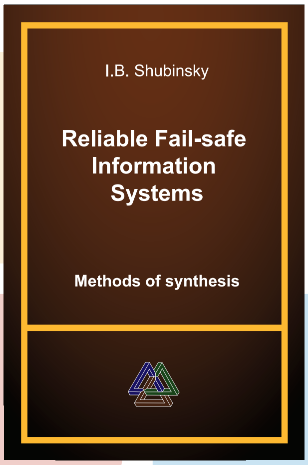
# SUBSCRIPTION TO THE JOURNAL «DEPENDABILITY»

It is possible to subscribe to the journal:

- Through the agency «Rospechat»
– for the first half of the year: an index 81733;

- Under the catalogue "Press of Russia" of the agency «Books-services»:
– for half a year: an index 11804;

- Through the editorial office:
– for any time-frame
tel.: 8-916-105-81-31; e-mail: E.Patrikeeva@gismps.ru



I.B. Shubinsky
Reliable Fail-safe Information Systems
Methods of synthesis

## SUBSCRIBER APPLICATION FOR DEPENDABILITY JOURNAL

**Please subscribe us for 20___**
**from No. ________ to No._______ number of copies _________**

| | |
|---|---|
| **Company name** | |
| **Name, job title of company head** | |
| **Phone/fax, e-mail of company head** | |
| **Mail address (address, postcode, country)** | |
| **Legal address (address, postcode, country)** | |
| **VAT** | |
| **Account** | |
| **Bank** | |
| **Account number** | |
| **S.W.I.F.T.** | |
| **Contact person: Name, job title** | |
| **Phone/fax, e-mail** | |

**Publisher details: Dependability Journal Ltd.**
Address of the editorial office: office 209, bldg 1, 27 Nizhegorodskaya Str., Moscow 109029, Russia Phone/fax: 007 (495) 967-77-02, e-mail: E.Patrikeeva@gismps.ru
VAT 7709868505 Account 890-0055-006
Account No. 40702810100430000017
Account No. 30101810100000000787

**Address of delivery:**

**To whom:**______________________________________________

**Where:**________________________________________________

To subscribe for Dependability journal, please fill in the application form and send it by fax or email.
In case of any questions related to subscription, please contact us.
Cost of year subscription is 4180 rubles, including 18 per cent VAT.
The journal is published four times a year.