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Investigation and Assessment of the Influence of Repairs on Transport System Operation Efficiency and Reliability

Łukasz Muślewski*
Maciej Woropay*
Piotr Bojar*

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Abstract

Transport systems, especially transport means operated by them, generate different types of threats: peoples' health and life threat and natural environment degradation threat. Operating factors affecting elements of technical objects cause negative value changes of these elements resulting in their failure. These factors include those which result from improper behavior of people and those connected with the environmental impact affecting the technical object. Failure is a circumstance which significantly decreases the vehicle reliability and efficiency.

In this study, a failure is referred to as exceeding permitted boundary values by significant features of the technical object. On the basis of performed practical tests concerning times of a failure occurrence it was found that the set of failures can be divided into subsets of primary and secondary ones. Tests results revealed that the cause of occurrence of secondary failures are usually incorrect performance of primary repairs. Primary repairs are independent on each other and occur randomly. Secondary failures, in turn, are related to each other and their occurrence is conditioned by an earlier occurrence of a primary failure and the effect of its improper repair or a repair of a successive secondary one. Therefore, assurance of high efficiency of repairs performed on the transport means is of great importance as this affects the level of reliability, safety and efficiency of transport tasks.

* University of Technology and Life Sciences Bydgoszcz, Poland

1. Introduction

The authors this work make an attempt to make an assessment of the influence of failures occurring in the process of means of transport operating on reliable and efficient functioning of transport means. A failure of a technical object has been defined as exceeding permitted boundary values by significant features describing its elements.

On the basis of literature and results of the authors' own research it was found that a failure of transport means used in transport systems are the effect of the impact of different forcing factors [13].

Some failures result from the natural wear of elements of machines, whereas others can be caused by incorrectly performed repairs of a previous failure. In effect of this, there occur the so called secondary failures in a short period of time. They result from improper organization of repairs, poor skills of mechanics, limitations connected with pre-repair and post repair diagnosing, etc.

As it can be seen in Fig. 1, repair errors account for one of the most frequent causes of occurrence of transport means subsystems failures. A comparison of significant causes of transport means failure occurrence has been show in Fig. 1.

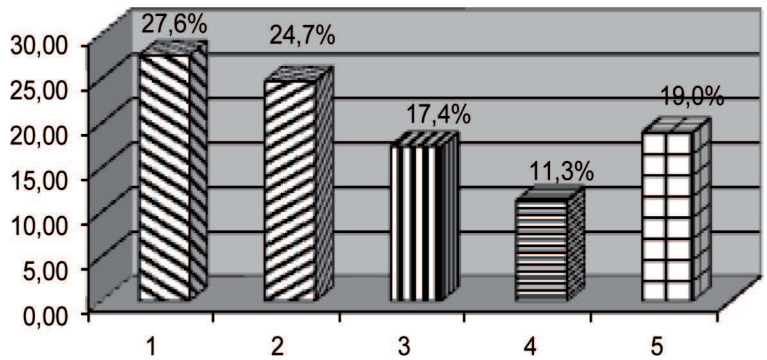

Fig. 1. Frequency of occurrence of transport means elements failures, 1. Repair errors, 2. Operation errors, 3. Environmental impact, 4. Failure of cooperating elements, 5. Others

2. Research Object and Subject

The research object are subsystems of vehicles operated in a municipal transport system. Whereas, the research subject are failures of transport means selected subsystems and times of their occurrence.

3. Failure and Repair of Technical Objects

During practical tests performed in a real system of transport means there were carried out investigations on time intervals between successive failures of transport means subsystems and times of their occurrence. During the analysis of times of transport means failures occurrence it was found that there was a difference between theoretical and practical distributions of values of time intervals occurring between these times (Fig. 1).

A significant difference between the theoretical and practical distributions at the beginning of (0, t_p) interval, decreases to zero from times p. However, in (t_p, ∞) interval the theoretical function is consistent with the empirical distribution. This discrepancy results from occurrence of the so called secondary failures being effects of inappropriate quality of primary repairs in interval (0, t_p). The tests prove that times of secondary failures are contained in the interval 0 to 7 days (Fig. 1).

The analysis of empirical data (length of time intervals between failures) proves purposefulness to describe times of correct operation probability distribution with reliability function $R(x)$, in the form as follows:

$$R(x) = pe^{-\lambda x} + (1 - p) R_w(t) \tag{1}$$

It is a mixture of exponential distribution $pe^{-\lambda x}$ with an unknown value of parameters $(p\lambda)$ with reliability function $R_w(t)$. Estimation of parameters of distribution $(p\lambda)$ with reliability function described by dependence (1), is a complex problem.

Assuming that for an unknown distribution (of correct operation times) focused on limited time interval (0,t), it is possible to estimate values of parameters p and λ, then for high values, it can be assumed that $R(t) \approx p * exp(-\lambda t)$. Thus, using linear regression methods (in a semi-logarithmic system) values of parameters p and λ can be determined for different random tests, cut from the bottom. For each such approximation the error of standard regression is calculated $-S(i)$, where i denotes the index of the day from which data is analyzed.

The analysis of $S(i)$ course in dependence on the value shows that there is a minimum $s(i)$ for different i, most often for i = 5,6,7,....12 [2,5].

The course of a real function can be described by a mixture of probability distributions with $g(t)$ density with exponential distribution.

Let $\tau_i(k)$, where $i = 0, 1, 2, \ldots, \tau_0(k) = 0, k = 0, 1, 2, \ldots, n$ denote a stream (times) of k-th technical object failures.

Difference $\tau_{i+1}(k) - \tau_i(k)$ for $i = 0, 1, 2, \ldots,$ denotes length of time interval between $i+1$-th i-th failure of k-th technical object.

$Y_i(n)$ denotes superposition of n –the number of failure.

Let $X_i(n) = Y_i(n) - Y_{i-1}(n)$, where $i = 0, 1, 2, \ldots, Y_0 = 0$

It is assumed that the distribution of $X(i)$ random variable does not depend on i.

According to Grigelionis formula, random variable $X(n)$ has exponential distribution with $n \to \infty$.

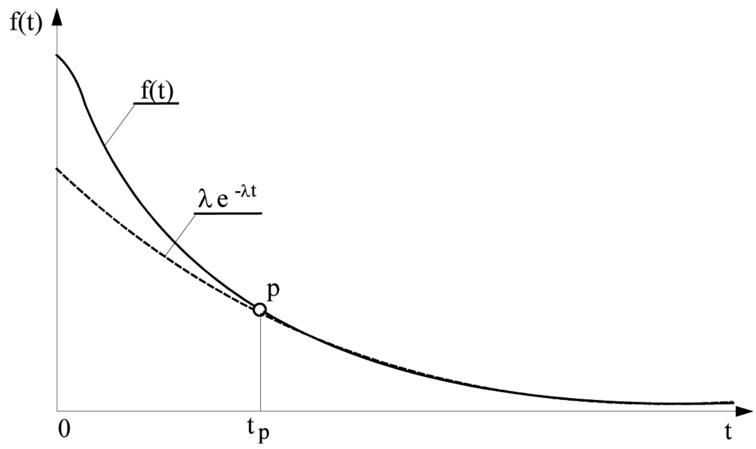

Fig. 2. Changes of exponential and real function values in time t

It is assumed that probability density of random variable T has the form as follows:

$$f(t) = \alpha \cdot g(t) + (1 - \alpha) e^{-\lambda t} \quad \text{for} \quad f(t) \geq 0 \tag{2}$$

It is a mixture of probability distribution with density $g(t)$ with exponential distribution with density given by dependence (2):

$$g_1(t) = \lambda \cdot e^{-\lambda t} \tag{3}$$

Estimation of parameter α and density λ (2) is based on the assumption that density $g(t)$ assumes values higher than zero and relatively low within the interval from $\langle t_p, \infty \rangle$.

The analysis of results of practical tests on times of failure occurrence, proves that the set of failures can be divided into subsets of primary and secondary failures.

Thus, the successive times of failure of the same subsystems concentrate in a sequence after occurrence of a single event.

An exemplary stream of failures of the transport means selected subsystem, has been presented in Fig. 3.

As it can be seen in Fig. 3, the first of the failures which occurred in time Ti, causes a sequences of successive failures of the same subsystem in short time intervals. These failures are called primary ones.

The successive ones, with a finite number of repetitions, occurring in times t_{ij}, are referred to as secondary failures. Basing on the tests results analysis it was found that the cause of secondary failure occurrence is usually inappropriate quality of repairs of the subsystem element primary failures

Primary failures do not depend on each other and occur randomly (are not related to each other by a cause-effect connection). Secondary failures are dependent

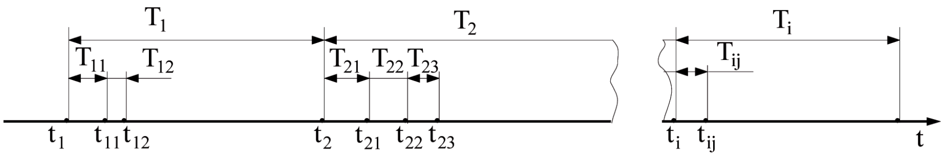

Fig. 3. Time intervals between primary and secondary failures
t_i – times of primary failures occurrence,
t_{ij} – times of secondary failures occurrence,
T_i – time intervals between times of primary failures occurrence,
T_{ij} – time intervals between secondary failures occurrence times.

on each other because their occurrence is conditioned by earlier occurrence of a primary failure and the effect of its inappropriate repair or inappropriate repair of the next secondary failure.

Reduction of conditional probability of secondary failure occurrence can be a point of reference for a decrease in the failure intensity. It can be achieved through elimination of failures occurring due to irrational execution of the repair process.

4. Modeling Process of Failure Occurrence Times

In result the analysis of transport means failure occurrence times and values of time intervals contained between them, an estimation of the real process parameters values was performed. On this basis, there was built a simulation model representing a real stream of failures, studying of which enables an assessment of effectiveness of repairs carried out in the service process.

In Fig. 4, a dialogue window of the simulation program by means of which values of the real process are introduced to the simulation model, has been presented.

On the basis of an analysis of the subject literature and results of the authors' own tests a generalized Gamma [3] distribution was accepted for the simulation program of transport means failure stream. By means of accepted values of parameters (b-parameter of scale, p-parameter of shape, v-parameter of shape) of this distribution, time intervals between times of primary failure occurrence were simulated. For values of parameter $v = 1$, time intervals were generated according to Gamma distribution. Whereas, for parameters with values $p = 1$ and $v = 1$ time intervals were generated according to exponential distribution.

Random variable X has gamma distribution if its density is expressed by formula (4):

$$f(x) = \frac{1}{bp\Gamma(p)} \cdot x^{p-1} e^{-\frac{x}{b}} \quad x>0, \quad p,b>0, \tag{4}$$

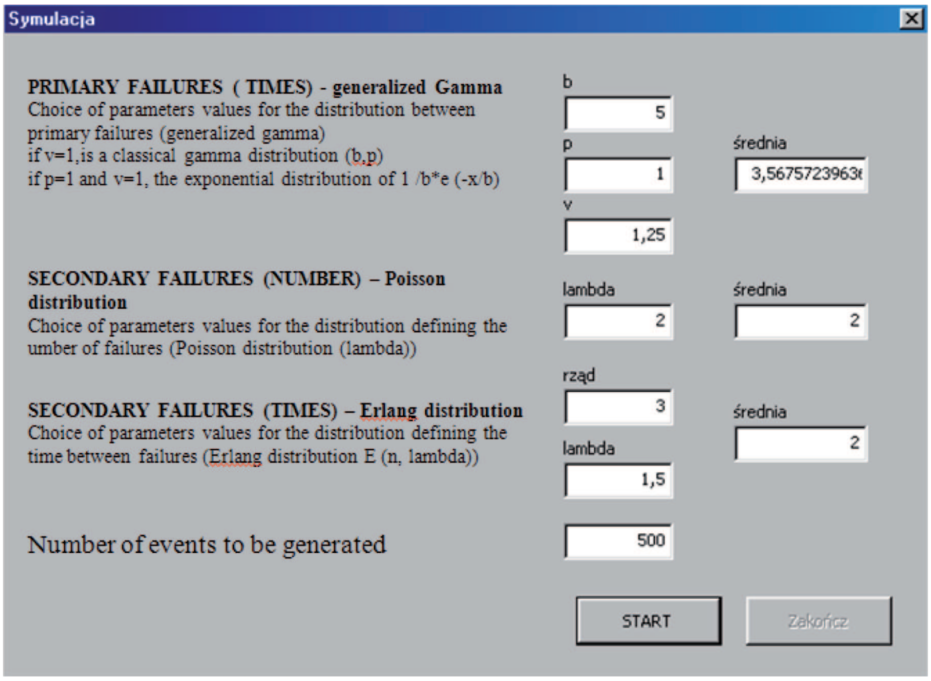

Fig. 4. Dialogue window of a simulation program

where: $\Gamma(p)$ is gamma function expressed by formula (5):

$$\Gamma(p) = \int_0^\infty x^{p-1} e^{-x} dx \tag{5}$$

If $p = 1$, then we have exponential distribution as a special case. When parameter p is a an integrity, gamma distribution is Erlang distribution. Parameter p is a parameter of shape, whereas, parameter b is a parameter of scale. Mean value EX is expressed by dependence (6):

$$EX = pb \tag{6}$$

variance, by formula (7):

$$D^2 X = pb^2 \tag{7}$$

Equations (6 and 7) can be a basis for construction of estimators p and b as well as parameters p and b. From these equations, it results that:

$$\hat{b} = \frac{s^2}{\bar{x}}, \quad \hat{p} = \frac{\bar{x}}{\hat{b}} = \frac{(\bar{x})^2}{s^2} \tag{8}$$

If a new variable is defined:

$$T = x^{\frac{1}{v}}, \quad v>0 \tag{9}$$

random variable T has a generalized gamma distribution with probability density, expressed by dependence (10):

$$f(t) = \frac{v}{b^p \Gamma(p)} \cdot t^{pv-1} e^{-\frac{t^v}{b}} \tag{10}$$

Density of generalized gamma distribution is also presented in paper [3] in the following form:

$$f(t) = \frac{v}{-b\Gamma(p)} \left(\frac{t}{b}\right)^{pv-1} \exp\left\{-\left(\frac{t}{b}\right)^{v}\right\}, \quad t>0. \tag{11}$$

Mean value of this distribution is expressed by formula (12)

$$ET = b\frac{\Gamma\left(p + \frac{1}{v}\right)}{\Gamma(p)}, \tag{12}$$

whereas, variance by formula (13):

$$D^2T = b^2\left(\frac{\Gamma\left(p + \frac{2}{v}\right)}{\Gamma(p)} - \frac{\Gamma^2\left(p + \frac{1}{v}\right)}{\Gamma^2(p)}\right) \tag{13}$$

Estimation of this distribution is given in work [3].

Random numbers of generalized Gamma distribution(three parameters: b, p, v) are obtained as random numbers from gamma distribution with parameters b and p which are raised to power $\frac{1}{v}$.

Whereas, random numbers of Gamma distribution (b, p) are obtained by means of an inbuilt function of program Excel, distribution gamma (it is a realization of random numbers generated from Gamma distribution (b, p), through reversing distribuants of this distribution).

$$r(b, p, v) = (\text{Gamma}(b, p))^{\left(\frac{1}{v}\right)} \tag{14}$$

The number of secondary failures which occur in a sequence of events after the primary failure (Fig. 3) was generated according to Poisson distribution with a defined value of parameter λ (expected value).

Random numbers from Poisson distribution are obtained by means of the algorithm:

- for established λ, $q = e^{-\lambda}$ is computed,
- $x = 0$, $S = q$ and $p = q$ are established,
- random number r is generated from even-armed distribution on section *[0, 1),*
- until $r > S$:

$x = x+1;$
$p = p^*\lambda/x;$
$S = S + p;$
are calculated, successively.

When S is bigger or equal to r, value x is accepted to be a number from Poisson distribution with parameter λ.

Time intervals between secondary failures have been generated from Erlang distribution with defined values of parameters of this distribution, such as: r the number of secondary failures occurring in a sequence after the primary failure and value of parameter λ.

Random numbers from Erlang distribution with parameters n and λ are obtained using formula (15):

$$r(n,\lambda) = \sum_{k=1}^{n}\left(-\frac{1}{\lambda}\ln(rnd)\right) \tag{15}$$

where:

rnd – is a random number of an even-armed distribution (uniform) on section [0,1).

The number of events, in a stream of events generated by means of a simulation program, was established having analyzing real streams of failures of transport means subsystems. In order to make an assessment of operation efficiency and reliability, values of reliability and efficiency indexes, selected on the basis of literature, were determined.

Mean mileage between two successive failures expressed by dependence (16):

$$L_k = \frac{1}{n}\sum_{i=1}^{n} l_{ki} \tag{16}$$

where:

n – number of mileages between failures of technical objects,

l_{ki} – i-th mileage between failures of the technical object.

Mean time of correct operation between two successive failures defined by dependence (17):

$$\Theta_k = \frac{1}{n}\sum_{i=1}^{n} t_{ki} \tag{17}$$

where:

n – number of analyzed objects, each of which being after k-1 repair,

t_i – time of the i-th object serviceability state until completion of k-1 repair until occurrence of k-th failure.

5. Results of Practical Tests

The analysis involved failures of selected subsystems of buses which were accepted as the most significant in terms of repair effectiveness assessment and their influence on the analyzed system operation reliability, efficiency and safety. Practical tests were carried out with the use of a passive experiment method in real conditions of transport means operation. The tests also covered a five-year-period of buses operation. They accounted for identification of factors affecting occurrence of secondary failures.

On the basis of accepted criteria, a classification of failures was made and basic static parameters were determined, such as: numbers of primary failures (L_{up}), numbers of secondary failures (L_{uw}) and mean values of time intervals between primary and secondary failures.

On the basis of known values of selected statistics of correct operation real times distribution, streams of failures with approximate values of parameters of statistics were determined in relation to values of statistics determined basing on empirical data [6].

Table 1

Values of the repair efficiency index for selected subsystems, expressed in %, for different numbers of secondary failures L

	The subsystem code				
	IE	PN	NA	SI	HA
Real value of the repair efficiency value	32,6	35,7	30,2	30,3	36,3
Value of the repair efficiency index for simulate data consistent with actual data.	32,4	35,6	30,1	30,4	36,3
Value of the repair efficiency index for a number of secondary failures reduced by 25%.	39,0	42,1	39,0	38,6	43,5
Value of the repair efficiency index for a number of secondary repairs reduced by 50%	48,9	51,3	47,2	45,8	49,8
Value of the repair efficiency index for a number of failure reduced by 75%	65,9	68,2	63,7	59,8	66,4
Value of the repair efficiency index for a number of failure reduced by 100%	100	100	100	100	100

As the table 1 shows, elimination of secondary failures in 100% causes a increase in the repair efficiency index to a unity. Whereas, elimination of the number of secondary failures by 25%, 50% and 75%, causes an increase in the efficiency index number, which is directly reflected by an increase in reliability and efficiency of the studied system operation reliability and efficiency.

6. Conclusions

On the basis of the carried out tests it can be concluded that secondary failures of particular elements or subsystems being the sequence of improperly performed repairs should be eliminated in the service process, increasing, thereby, reliability, safety and efficiency of the considered transport systems, especially their operation quality.

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