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RESEARCH ON EFFECTIVENESS OF TRANSPORT MEANS OPERATIONAL RELIABILITY AND EFFICIENCY REPAIRS

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Abstract

Systems of transport means operational use are such systems whose main goal is to carry out transport tasks on an assigned territory. In each transport system assurance of the used transport means availability, viewed as the object capability to accomplish the transport task, is of great importance. A certain number of damages results from natural wear of transport means elements which is a natural phenomenon, whereas other damages can be caused by ineffective repair of the previous damage. In this way, within a short time, there occur the so called repetitive damages to the repaired element. This reflects improper organization of repairs, poor skills of the maintenance workers, limitations connected with wrong diagnosing before and after the repair. Damages occurring during means of transport operation involve bearing considerable costs while assuring the transport means operational reliability, as well as covering the losses connected with impossibility to accomplish the transport task. Finding out the causes of ineffective repairs would reduce the costs that a transport company has to bear to provide efficient operation of means of transport.

Times of resultant repairs and being unfit for use have been analyzed, as well as costs of repairs, spare parts, maintenance and operation.

Keywords: *transport system, reliability, efficiency, failures, simulation model*

1. Introduction

It has been attempted in this paper to elaborate a model of the moments in which damages to the means of transport occur in the process of their use. Damage to a technical object has been defined as exceeding admissible limiting values by significant values of the features describing its elements.

On the basis of relevant references analysis and the results received from our own investigations it was found that the damages to the means of transport used in the transport systems result from various forcing factors affecting them [8].

Some number of the damages results from natural wear of the means of transport elements, which is a natural phenomenon, while the remaining damages may be caused by an inefficient repair of the previous damage. This leads to so called repetitive damages to the repaired element, occurred within a short time interval, which is a proof of inappropriate organization of the repairs, poor training level of the repairing teams, limits related to pre and after repair diagnosis, etc.

Within the framework of the operation and maintenance investigations performed in a real operation and maintenance system of the means of transport the time intervals occurring between the successive damages to the means of transport and the moments in which they occur were analysed.

On the basis of the analysis of the investigation results it has been found that, in general, the reason for the repetitive damages is inappropriate quality of the repairs of the primary damages, subsystem elements [16]. The primary damages do not depend on one another and they occur randomly (they are not related to one another with the cause and effect links). The repetitive damages are interdependent, because their occurrence depends on a previous occurrence of a primary damage and on the result of its inappropriate repair or inappropriate repair of the successive repetitive damage.

It means that the repetitive damage occurrence probability B_{tij} conditioned by a primary damage occurrence A_{ti} is greater than the primary damage occurrence probability A_{ti}.

Reduction of the conditional repetitive damage occurrence probability may be a starting point for reduction of the damage intensity, which leads to the increased level of the performed repairs efficiency. This may be achieved by elimination of those damages which occur due to unreasonable realization of the repair process.

The following definition of the repair efficiency has been adopted on the basis of the analysed references [15]:

„Repair efficiency – is a goal realization degree, in which such a repair should be finished, without considering its economic aspects. The specific repair of the investigated subsystem is considered to be efficient, if it gets closer, in more positive way, to the specified goal being the assurance of the system task ability to accomplish the task within specified time interval."

The aim of this paper is to build a simulation process model of the moments in which damages occur to the means of transport enabling generation of the damage streams, the analysis and evaluation of which will make it possible to undertake reasonable actions aimed at increasing the efficiency level of the repairs being realized, which result in rise quality improvement, especially of the transport means operational reliability and efficiency of the whole system operation.

2. Investigation object

All the considerations deal with the transport systems performing transportation of passengers and cargo over water, land and air routs. The main operation aim of such systems is realization of transport service within a specific environment, within specific quantity and within specific time by means of technical objects being operated and maintained within the system range. Therefore, evaluation and assuring their required operation quality, both in terms of safety, efficiency, reliability, readiness with simultaneous giving consideration to the economical aspect, forms an essential factor in the process of operating and maintaining them. The investigated transport systems belong to the group of the socio-technical systems of <H–M–E> (human – machine – environment) type, in which evaluation of their operation quality is performed depending on the changes of the feature values describing the action of the operators, technical objects controlled by them and the influence of the environment.

3. Investigation methodology

The investigations were performed within an urban transport system. The operation and maintenance investigations concern the damages to the subsystems of the means of transport and the moment in which they occur. These investigations were performed using a passive experiment method in real operation and maintenance conditions. A set consisting of 28 means of transport used in real operation and maintenance conditions was randomly selected for the investigation purposes. The investigation results cover five-year long vehicle operation and maintenance period.

4. Introduction to the problem of repetitive damages

When analysing statistically the moments the damages to the means of transport occur, a difference between the theoretical distribution and empiric one of the time interval values occurring between these moments (Fig. 1) was observed. The significant difference, between the theoretical distribution and the empiric one occurring at the beginning of the interval $(0, t_p)$ from the moment p, declines to zero. However inside the interval (t_p, ∞) the theoretical function is consistent with the empiric distribution. This discrepancy results from the repetitive damages caused by improper quality of the repairs of the damaged elements that occurs in the interval (0, t_p). The investigations prove that the moments of the repetitive damages are included inside the interval from 0 to 7 days.

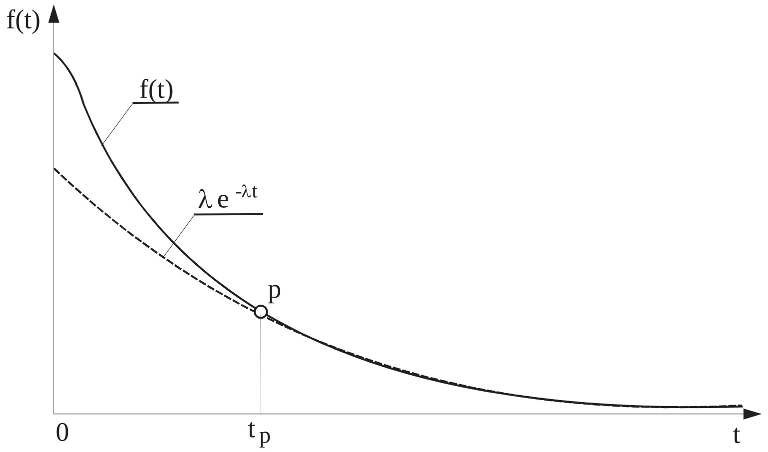

Fig. 1. Changes of the value of the exponential function and the real function at the time t

The analysis of the empiric data (the length of the time intervals between the damages) indicates that it is reasonable to describe the probability distribution of the correct work times with the reliability function $R(x)$ formulated as follows [1]:

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

It is a combination of the exponential distribution $pe^{-\lambda x}$ (with unknown value of the parameters ($p\lambda$) and the reliability function $R_w(t)$. The estimation of the distribution parameters ($p\lambda$) with the reliability function described with the dependence (1) is a complex problem.

Assuming that for unknown distribution (times of correct work) focused on the limited time interval (0, t_p) it is possible to estimate the values of the parameters p and λ, then for high values of t it may be assumed that: $R(t) \approx p \cdot \exp(-\lambda t)$. In that case using the methods of the linear regression (in the semi-logarithmic system) the values of the parameters p and λ may be evaluated for different random tests cut off from the bottom. For each such a approximation a regression standard fault is calculated – $S(i)$, where i stands for the index of the day from which the data are analysed. The analysis of the changes $S(i)$ depending on the value of i indicates that there is a minimum $s(i)$ for various i, most frequently for $i = 5, 6,..., 12$.

The changes of the real function may be described by a combination of the probability distribution with density $g(t)$ and exponential distribution.

Let $\tau_i(k)$, where $i = 0, 1, 2, \ldots$, $\tau_0(k) = 0$, $k = 0, 1, 2, \ldots, n$ stand for the stream (moments) of the damages of the k-th technical object.

The difference $\tau_{i+1}(k) - \tau_i(k)$ for $i = 0, 1, 2, \ldots$, stands for the length of the time interval between i+1-st and i-th damage of the k-th technical object.

$Y_i(n)$ denotes superposition n – of the damage streams.

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 the random variable $X_i(n)$ does not depend on i.

According to the theorem of Grigelionis it is known that with $n \to \infty$ the random variable $X(n)$ has exponential distribution.

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

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

It is a combination of the probability distribution with the density $g(t)$ and the exponential distribution with the density given with the formula (3):

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

The estimation of the parameter α and λ of the density (3) is based on the assumption that the density $g(t)$ takes the values above zero, and that they are relatively low and included within the range from $\langle t_p, \infty\rangle$.

The analysis of the results of the operation and maintenance investigations regarding the moments the damages occur prove that the set of the damages may be divided into subsets of the *primary* and *repetitive* damages.

It results from the fact that the consecutive moments of the damages to the same subsystems are gathered sequentially after a single damage occurred. The Fig. 2 shows an exemplary damage stream of a chosen subsystem of a mean of transport.

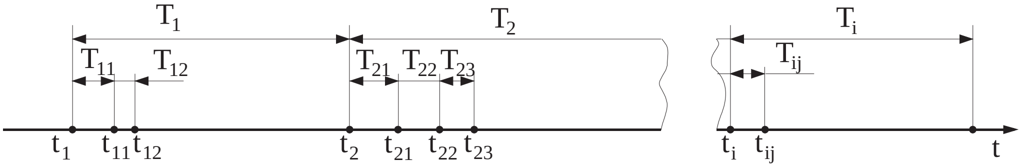

Fig. 2. Time intervals between the primary and repetitive damages, t_i *– the moments the primary damages occur,* t_{ij} *– the moments the repetitive damages occur,* T_i *– the time intervals between the moments the primary damages occur,* T_{ij} *– the time intervals between the moments the repetitive damages occur*

As it is shown in the Fig. 2, the first of the damages which occurred at the moments t_i, cause the sequences of the subsequent damages to the same subsystem within short time intervals. These damages are called *primary*. Whereas the next of them, with the finite number of repetitions occurring at the moments t_{ij}, is called *repetitive*. Based on the analysis of the investigation results it has been found that the reason for the repetitive damages is, in general, improper quality of the repairs of the primary damages to the subsystem elements.The primary damages are independent on one another and they occur randomly (they are not connected with one another by the cause and effect links). The repetitive damages are dependent, because their occurrence depends on prior occurrence of the primary damage and the effect of its improper repair or improper repair of the next repetitive damage.

Reduction of the probability of the occurrence of a repetitive damage may be an initial point for reducing the damage intensity. It may be achieved by eliminating the damages occurring due to unreasonable realization of the repair process [5].

It should be mentioned that according to transport means damage classification criteria, accepted in [16] work, they have been classified into subsets of primary and repetitive repairs.

Damages to selected subsystems were classified according to the basic criterion and an auxiliary one, determined on the basis of mean values for times of correct operation between these damages.

5. Process model of the moments in which the damages occur

Because of impossibility to carry out long-term operation and maintenance investigations as well as due to difficulties to implement changes to the repair process of the means of transport system a simulation model of the moments in which the damages occur was built to facilitate generation of the streams of the damages to the means of transport. The analysis and evaluation of the results obtained at the simulation stage will enable to evaluate the efficiency of the repairs being realized in a real transport system.

By analysing the moments in which the damages to the means of transport occur and the values of the time intervals between them, the real process parameter values were estimated.

This was the basis for creating a simulation model representing a real stream of the damages, which, when being examined, enables to evaluate the efficiency of the repairs realized within a service process.On the basis of the relevant references and the results of our own investigations the generalized Gamma distribution [2] has been adopted to generate, in the simulation program, the streams of the damages to the means of transport subsystems. By means of the adopted parameter values (b – scale parameter, and p – shape parameter, v – shape parameter) of this distribution, the time intervals between the moments in which the primary damages occur were simulated in the program. In case of adopting the values of the parameter $v = 1$, the time intervals were generated according to the Gamma distribution. However, for the parameters with the values $p = 1$ and $v = 1$ the time intervals were generated according to the exponential distribution.

The random variable X has gamma distribution, if its density is expressed by the following formula (4):

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

where $\Gamma(p)$ is a gamma function expressed with the formula (5):

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

If $p = 1$, then we have an exponential distribution as a particular case. In case when the parameter p is an integer number, then the gamma distribution is the Erlang’s distribution. The parameter p is the form (shape) parameter, while the parameter b is the scale parameter.

The average value EX is expressed with the following relation (6):

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

and the variation with the formula (7):

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

The equations (6, 7) may form the basis for creating estimators $\hat{p}$ and $\hat{b}$ of the parameters p and b. It results from these equations that:

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

If we define a new variable:

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

then the random variable T has generalized gamma distribution with the probability density expressed with the relation (10) as follows:

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

The density of the generalized gamma distribution is stated in this paper in the following form:

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

The average value of this distribution is expressed with the formula (12):

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

and the variation with the formula (13):

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

The estimation of this distribution parameter has been stated herein [2].

The random numbers coming from the generalized Gamma distribution (three parameters: *b, p, v*) are obtained as random numbers coming from the gamma distribution with the parameters *b* and *p*, which were raised to the 1/*v* power.

The random numbers out of the Gamma distribution (*b, p*) were obtained by means of the GAMMAINV function built in the EXCEL 2000 program (it is a realization of the generator of the random numbers out of the Gamma distribution (*b, p*) by inverting the distribution function of this distribution).

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

The number of the repetitive damages occurring in the sequence of the events after the primary damage (Fig. 2) was generated according to the Poisson's distribution with specified value of the parameter λ (expected value).

The random numbers coming from the Poisson's distribution are obtained by means of the following algorithm:

- $q = e^{-\lambda}$ is calculated for the determined λ,
- $x = 0$, $S = q$ and $p = q$,
- a random number *r* is generated out of the uniform distribution over the range [0, 1),
- as long as $r > S$ the following parameters are calculated: $x = x + 1$, $p = p*\lambda/x$, $S = S + p$.

When *S* becomes greater or equal to *r* the value of *x* is adopted as a number out of the Poisson's distribution with the λ parameter.

The time intervals between the repetitive damages were generated out of the Erlang's distribution with the defined values of the parameters of this distribution, such as: number of the repetitive damages occurred in the sequence after a primary damage and the value of the parameter λ.

The random numbers out of the Erlang's distribution with the parameters *n* and λ are obtained on the basis of the following formula (15):

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

where *rnd* is a random number out of uniform (rectangular) distribution over the range [0, 1).

The number of the events, in the damage stream generated by the simulation program, was determined on the basis of the statistical analysis of the real streams of the damages to the subsystems of the means of transport.

6. Chosen investigation results and verification of the model adequacy

On the basis of the analysis of a real stream of the damages to the selected means of transport subsystem, the damages were classified according to the adopted criteria (value of the limiting distance travelled expressed in kilometres and the critical time of correct work) to the subset of the primary or repetitive damages. Due to the analysis carried out, the average times of correct work between the damages were determined. The determined statistics were entered to the simulation model (Tab. 1) and the damage streams with similar parameters of the statistics, if compared to the statistics determined on the basis of the empiric data, were generated with its help [14].

Tab. 1. Exemplary values of the parameters adopted to simulate a stream of the damages to the electric installation subsystem

Name or parameter symbol	Value
b - scale parameter	1.073
p - shape parameter	19.985
v - shape parameter	0.902
λ - number of repetitive damages	2.14
row	1.87
λ	0.3924
number of damages	115
T_1 - average time of correct work between the primary damages	22.9026
T_2 - average time of correct work between the repetitive damages	4.8295

In order to verify consistency of the real damage stream and the one generated by the simulation program, Kolmogorov-Smirnov goodness of fit test being used in case of small number of tests was applied. The goodness of fit test was used in order to check the consistency of the hypothesis saying that two tests have the same distribution. The differences between both distribution functions were considered in this test. The limiting distribution of the appropriate statistics, used to build the critical range for this test, is the same as limiting distribution of the statistics λ by Kolmogorov.

The critical value λ_α was read from the table of this distribution for the predefined significance level $\alpha = 0.95$ to have $P\{\lambda \geq \lambda_\alpha\} = \alpha$, when the calculated value of the statistics λ meets the inequality $\lambda \geq \lambda_\alpha$. The hypothesis H_0 was rejected because both tests have different distributions. However in case, when $\lambda < \lambda_\alpha$, there are no grounds to reject the hypothesis saying that the distributions of both tests are the same. The limiting value λ_α for the adopted value of the significance level α is λ_α=1.358.

In case when the distribution consistency was found a damage stream in which the primary and repetitive damages existed was simulated according to the previously adopted values of the parameters, as stated in the Tab. 1.

The value of the repair efficiency index of the *j*-th subsystem is described with the relation [3]:

$$WS_j = \frac{N_j(t) - N_j^{N}(t)}{N_j(t)} = \frac{N_j^{S}(t)}{N_j(t)}, j = 1, 2, ..., m \ . \tag{16}$$

The next step was to simulate, by means of the program, improvement of the efficiency of the repairs being realized by reducing the value of the parameter λ by 25% each time, as it is presented in the Tab. 2.

In order to evaluate operation efficiency and reliability, the values of the selected reliability and efficiency factors were determined based on the references in question.

The average distance travelled between two consecutive damages is expressed with the dependence (17):

$$L_k = \frac{1}{n}\sum_{i=1}^{n} l_{ki} , \tag{17}$$

where:
n - number of runs between the damages to the technical objects,
l_{ki} - i-th run between the damages to the technical object.

Average time of correct operation between two consecutive damages is described with the dependence (18):

$$\Theta_k = \frac{1}{n}\sum_{i=1}^{n} t_{ki} , \tag{18}$$

where:
n - number of investigated objects, of which each underwent k–1 repair,
t_i - time range at which the i-th object is serviceable from the moment of completing k–1 repair up to the occurrence of the k-th damage [15].

Tab. 2. Values of the model parameters adopted to simulate the streams of a selected subsystem for different number of repetitive damages L_{uw}

Name or parameter symbol	Value 100% L_{UW}	Value 75% L_{UW}	Value 50% L_{UW}	Value 25% L_{UW}
b	1.073	1.073	1.073	1.073
p	19.985	19.985	19.985	19.985
v	0.902	0.902	0.902	0.902
λ	2.12	1.16	0.463	0
n	1.91	1.46	1.07	0.48
λ	0.3924	0.3924	0.3924	0.3924
N	1000	1000	1000	1000
T_1	22.9026	22.9026	22.9026	22.9026
T_2	4.8295	4.8295	4.8295	4.8295

In order to assess transport means operational efficiency, exemplary values for indexes which are described by dependencies [6] have been determined. For the purposes of the conducted research, only these indexes were taken into account that are connected with repairs and the vehicle diagnosing as they are one of the main factors that affect costs born by a transport company involved in provision of operational reliability for the used vehicles.

Index defining the share of costs of the used vehicle current repairs in the transport company overall costs (19):

$$W_1 = \frac{K_1}{\sum K} , \tag{19}$$

where:
K_1 - costs of current repairs,
$\sum K$ - total costs.

The index defining the share of the used vehicle daily maintenance (OC) costs in overall costs born by the transport company (20):

$$W_2 = \frac{K_2}{\sum K} , \tag{20}$$

where:
K_2 - costs of the used vehicle daily service,
$\sum K$ - overall costs.

The index defining the share of costs involved in services of the used vehicles in overall costs born by a transport company (21):

$$W_3 = \frac{K_3}{\sum K}, \tag{21}$$

where:
K_3 - costs of the used vehicle services,
$\sum K$ - overall costs.

In Table 3 there are presented results of tests concerning effectiveness of repairs and efficiency and reliability of transport means operation during carrying out the research.

Tab. 3. Values of indexes for effectiveness of repairs and efficiency and reliability of transport means operation in the same quarters of successive years

Year	WS	L_K	Θ_K	W_1	W_2	W_3
2006	33.82	2822.69	21.6914	14.50	2.27	2.12
2007	31.15	2516.19	18.4592	17.11	2.05	1.67
2008	34.25	3240.32	23.5224	13.70	2.46	2.53

From the data contained in Tab. 3, it results that an increase in ineffective repairs causes a decrease in the repair effectiveness index value of the tested vehicles. This in turn, results in an rise of the share of current repair costs in overall costs born by a transport company, with simultaneous fall of the values of index for: average mileage and average time between the successive repairs of the used transport means [6].

7. Summary

An important action to be taken in order to improve transport means operation efficiency and reliability is realization of feedback involving use of information on the repair effectiveness so as to eliminate factors that impair their quality:

- qualifications and involvement of the person who makes the repair,
- equipment of the repair stand,
- quality of materials used for the repair,
- organization of the repair process,
- influence of the environment,
- equipment of the diagnostic stand (diagnosing before and after repair),
- quality of control of the repairs.

Currently, works on creating universal efficiency indexes are being carried out. Maintenance and operation investigations involve defining value changes of these indexes, especially, determining the level of financial losses born by the transport company which have been caused by inappropriate operation and maintenance. Times of resultant repairs and being unfit for use have been analyzed, as well as costs of repairs, spare parts, maintenance and operation.

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