Journal of KONES Powertrain and Transport, Vol. 18, No. 3 2011

METHOD FOR ASSESSMENT OF TRANSPORT MEANS FAILURES REPAIRS

Łukasz Muślewski

University of Technology and Life Sciences
Prof. S. Kaliskiego Street 7, 85-789 Bydgoszcz, Poland
tel.: +48 523408723
e-mail: lukasz.muslewski@utp.edu.pl

Maciej Woropay

Air Force Institute of Technology
Księcia Bolesława Street 6, 01-494 Warsaw, Poland
tel.: +48 668 846 228

Andrzej Neubauer

Nicolaus Copernikus University
Gagarina Street 11, 87-100 Toruń, Poland
e-mail: aneub@umk.pl

Mirosław Szubartowski

„Karor" Sp. j.
Smoleńska Street 154, 85-871 Bydgoszcz, Poland
tel.: +48 52 362 01 21
e-mail: biuro@karor.com.pl

Abstract

An analysis of experimental tests and a literature survey of the issue revealed that the problems connected with assessment of costs and effectiveness of transport means repairs has a significant influence on their operation efficiency. Operating factors affecting the elements of technical objects cause negative changes in their features resulting in failures. The failures are referred to as events which significantly impair the vehicle operation efficiency, safety and reliability. On the basis of experimental tests concerning times of failures occurrence, it was found that the set of failures can be divided into subsets of primary and secondary failures. The tests results revealed that the most frequent cause of secondary failures occurrence was improperly performed primary repairs. Primary failures are not related to each other and they appear randomly. However, secondary failures are related to each other as their occurrence is conditioned by the primary failure and results from an inappropriate performance of the successive secondary failure. Basing on an analysis of the author's own tests results, it was established that failures of transport means used in real transport systems are the effect of impact of various forcing factors. Some failures result from the natural wear of machine elements, whereas, other failures can be caused by inappropriate repair of the previous damage. Thus, there occur the so called secondary failures in a short period of time. In connection with this, high efficiency of the repair performance is of primary importance as it largely affects efficiency of transport tasks accomplishment. In this article, there has been discussed a method developed for assessment of repair costs connected with elimination of secondary failures and its influence on the studied transport system operation efficiency. Familiarity with available technologies for repairs of primary failures as well as with costs of work and costs connected with technical equipment of the repair stations enables specification of the lowest costs necessary for reduction of the number of secondary failures and the average time of their repairs.

Keywords: *transport system, operation process, semi-Markov model, efficiency*

1. Analysis of the influence of effectiveness of repairs on transport means functioning efficiency

An analysis of carried out experimental tests and the subject literature reveals that the issue connected with an assessment of transport means repair effectiveness has a large influence on their operation efficiency. In the literature on the subject, the issue of technical objects repairs is reduced mainly to an assessment of the quality of maintenance and repair activities performed in subsystems which provide transport means with serviceability. However, the effects of secondary failures on the values of calculated indexes are not been analyzed yet [9].

The factors affecting operation and maintenance of the technical object elements cause negative changes in the elements significant values which leads to their failure. The forcing factors include those which result from improper actions of the humans and those which come from the environment. Failures are events which have a negative influence on efficiency, safety and reliability of the vehicle operation. On the basis of experimental tests concerning times of the failure occurrence it has been found that the set of failures can be divided into subsets of primary and secondary failures. The tests results reveal that the causes of secondary failures occurrence are usually incorrectly performed repairs of the primary ones. Primary failures are independent on each other, and they occur randomly. However, secondary failures are related to each other as their occurrence is conditioned by an earlier occurrence of a primary failure and the effect of its improper repair or an incorrect repair of another secondary failure. In connection with this, providing the transport means with high effectiveness of repairs is a crucial problem as it largely affects efficiency of transport tasks accomplishment. In this section, there have been presented experimental and simulation tests on the subject of the influence of elimination of transport means secondary failures on the transportation system operation efficiency and reliability.

2. Transport means damageability

Damage to a technical object has been defined as exceeding permitted boundary values by the object significant characteristics [9].

On the basis of the subject literature analysis and the authors' own research results it was found that failures of transport means used in transportation systems are the effect of the influence of different forcing factors. These factors can be divided into:

- working media – affecting the machine in result of the machine operation process (the machine conditioned functioning),
- external factors – characteristic for the environment influence on the machine (unconditioned operation of the machine),
- anthropological -technical factors – affecting the machine in result of conscious or unconscious actions of the human (e.g. human errors committed in the process of maintenance and operation.

Due to the nature of the influence of forcing factors on the technical object, they can be divided into two main categories:

- conditioned by the machine functioning (affect the machine only during its operation),
- unconditioned by the machine operation (affect the machine also when it does not operate).

Some number of failures results from a natural wear of the machine elements, whereas other failures can be caused by inefficient repair of a previous failure which leads to occurrence of the so called secondary failures, within a short time. They are the effect of:

- insufficient skills of the repair teams,
- limitations connected with pre and post repair diagnosing.

On the basis of the authors' own research analysis it was found that identification of the failure occurrence causes during transport means repairs plays a significant role in improving the quality of the operation reliability. The main causes of failures occurred due to repair errors include:

- application of inappropriate material,
- control errors,

- repair technology errors,
- application of an improper spare part,
- application of a damaged part,
- application of improper material,
- application of a part with a hidden technological fault,
- application of a part with improper dimensions,
- assembly errors,
- pollution after the repair.

An analysis of experimental tests reveals that a decrease in the number of secondary failures is a crucial problem whose solution provides a possibility to influence the level of transport means operation efficiency and reliability.

In connection with this, the research object involves failures of transport means subsystems. Therefore, the research subject is an influence of those failures on the transportation system operation efficiency and reliability.

3. Means of transport failure and repair

The experimental tests carried out in a real transportation system. Involved an analysis of time intervals between successive failures of the vehicle elements and their occurrence times [7].

A static analysis of transport means failure occurrence revealed that there was a difference between the theoretical and empirical distributions of values of time intervals occurring between these times. A significant difference between the theoretical and empirical distributions, at the beginning of interval (0,t) from time p, approaches zero. Whereas, within interval (tp, ∞) the theoretical function is convergent with the empirical distribution. The divergence results from occurrence, in interval (0,t) of the so called secondary failures, are result from improper quality of the damaged element repair.

The analysis of empirical data (length of time intervals between failures) proves purposefulness to describe the probability distribution of proper operation times by means of reliability function R(x) with the following form:

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

This is a combination of exponential distribution $pe^{-\lambda x}$ (with unknown value of parameters $(p\ \lambda)$ with reliability function $R_w(t)$. Estimation of distribution parameters $(p\lambda)$ with a reliability function, described by dependence (1), is a complex problem [8].

Assuming that for an unknown distribution (times of proper operation) concentrated within a limited time interval $(0, t_p)$ it is possible to evaluate values of parameters p and λ, then, for high values of t, it can be assumed that $R(t) \approx p*exp(-\lambda t)$. Thus, with the use of a linear regression method (in a semi-logarithmic system) it is possible to evaluate values of parameters p and λ for different random tests, cut at the bottom. For each such approximation, standard error of regression – $S(i)$ is calculated, where i denotes the index of the day from which data is analyzed. The analysis of course of S(i), in dependence on the value of 'i' , indicates existence of minimum s (i) for different i , most frequently for: i = 5,6,7,….,12.

The course of a real valued function can be described by a combination of probability distribution and density combination g(t) with an exponential distribution.

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

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

$Y_i(n)$ stands for superposition n of a stream of failures.

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 random variable $X_i(n)$ does not depend on *i*. On the basis of Grigelionis theorem it is known that with $n \to \infty$ random variable *X(n)* has an exponential distribution.

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

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

It is a combination of probability distribution and density g(t) with exponential distribution of density given by dependence (3).

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

Estimation of density parameters α i λ, is based on the assumption that density g(t) assumes values higher than zero and relatively low in the interval from ⟨tp, ∞⟩.

The analysis of experimental tests of failure occurrence times shows that the set of failures can be divided into subsets of primary and secondary failures [6].

It is due to the fact that the successive times of the same subsystem failures are concentrated sequentially after occurrence of a single failure.

A decrease in a conditional probability of a secondary failure occurrence can be a point of reference for reduction of intensity of failures. It can be obtained by elimination of failures caused by inappropriately performed repairs [7].

4. Failures classification methodology

Classification of transport means failures has been made for their particular subsystems. For this reason, the studied object was decomposed into subsystems. At the decomposition stage, there were accepted symbols of the transport means exemplary denotations which are presented in Tab. 1.

For the analysis of failures there were selected the so called significant subsystems (engine, braking system, wiring system), that is, those ones whose failure effects have the largest influence on transport means efficiency and reliability [7].

In order to classify failures into primary and secondary ones, there were introduced the following criteria [8]:

a) Basic criterion – mean mileage (in kilometres) between the successive failures of the j-th system, depending on:

L_u - Summary number of failures of the analyzed means of transport,
L_{u1} - number of failures of subsystem 1,
L_{u2} - numbers of failures of subsystem 2,
L_{u3} - numbers of failures of subsystem 3
L_{u5} - numbers of failures of the j-th subsystem,
P_c - the means of transport total mileage of during tests [km],
$L_{śrj}$ - mean mileage between two successive failures of the analyzed j-th subsystem failure [km], described by dependence (4):

$$L_{śrj} = \frac{P_c}{L_{uj}}, j = 1,2,3,4. \tag{4}$$

Standard deflection s_j' [km], is described by dependence (5):

$$s_j' = \pm\sqrt{\frac{\sum_{i=1}^{n}\left(L_{ij} - L_{śrj}\right)^2}{n-1}}, \quad \text{i= 1,2,…n,j = 1,2,3,4,5,} \tag{5}$$

where:

L - mileage between successive repairs [km] of the j-th subsystem,
n - number of measurements, that is, the number of mileages between successive repairs of the j-th subsystem.

Experimental tests were carried out in a real system of municipal transportation. They included research on failures of transport means subsystems and times of their occurrence. Failures of selected bus subsystems considered to be the most significant in terms of repair efficiency , were analyzed as well as their influence on each system operation reliability and efficiency Experimental tests were carried out with the use of a passive experiment method in real conditions of transport means operation. For the tests, a set of transport means performing transport tasks in real operation conditions was chosen randomly. The tests accounted for the factors affecting occurrence of secondary failures.

Basing on the accepted criteria, a classification of failures was made and values of the basic statistical parameters, such as: number of primary failures (L), number of secondary failures(L) and mean values of time intervals between them, were determined.

On the basis of known values of chosen statistics of distributions of correct operation real times, streams of failures with similar statistic parameters values as compared to statistic values established on the basis of empirical data, were generated [9].

5. Methodological aspect of secondary repair costs assessment

Knowledge of available technologies for repair of primary failures and labour costs and costs connected with equipment of repair stations enables specification of the lowest cost connected with a reduction of the number of secondary failures including the mean time of their repairs.

Change of technologies for repairs of primary failures can involve:

- equipment of repair stations with diagnostic and control devices,
- training repair staff,
- making payments depend on the index of repair quality computed after a certain period of time,
- specialization of the mechanics doing the primary repairs.

These actions being supposed to lead to a reduction of the secondary failures number and shortening of the repair duration mean time, involve additional costs (outlays) born by the system providing the vehicles with serviceability.

Using $\overline{T_{up}}$ to denote value of the primary failure repair mean time, $\overline{T_{uw}}$ to denote value of the secondary failure mean time and $\overline{n_{uw}}$ to denote the mean number of secondary failures generated by a single primary failure, makes it possible to present time dependencies characterizing repairs of primary and secondary failures, as in Fig. 1.

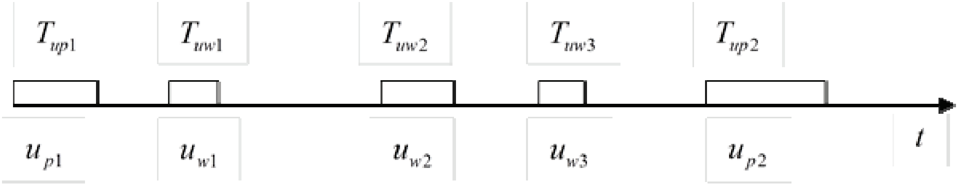

Fig. 1. Succession in time of primary and secondary failures with their duration times

Total time of secondary failures repairs in the period between two successive primary failures can be expressed (within a long time) as:

$$T = \overline{n_{uw}} \cdot \overline{T_{uw}}, \qquad (6)$$

where: T - stands for the total time of secondary repairs.

Analyzing benefits from the scale of outlay (growing effect of the outlay) it can be said that they occur when long-term mean costs decrease along with an increase in the outlay: Sustained benefits from the scale of expenditure (sustained effect of the outlay) occur when long term average costs are the same with an increase in the outlay.

However, disadvantages of the scale (the same effect of the outlays) occur when long-term average costs are the same, with an increase in expenditure.

The dependence of a unit costs increase or decrease along with a rise of expenditure, with established costs of the factors involved, is connected with the kind of applied technology, the repair, and its efficiency.

There are three groups of benefits from the scale of the outlay [1].

The first one in ‘indivisibility of the operation processes reflected by the system necessity to bear certain minimum expenditures necessary for its operation. this minimum is usually called a permanent cost.

Another group of causes of benefits from the scale of expenditure is connected with specialization which has a positive influence on the secondary failure repair quality.

The third group of causes is related to the previous one in the sense that with a big number of primary failure repairs the costs of repair station equipment are divided into many repairs which results in a reduction of a long-term mean cost.

On the basis of the above consideration, it can be said that the curve of mean costs connected with repair of secondary failures is U shaped. It means that with a significant increase in expenditures connected with a change of repair technologies for primary failures, a decrease in efficiency of the above mentioned repairs can be observed. In this case, a phenomenon of the scale disadvantage can be noted.

In connection with the above, there can be formulated a hypothesis that increasing costs of primary failure repair causes a reduction of the number of secondary failures and their duration times. This reduces costs of secondary failures repairs (despite additional costs of expenses connected with changing technologies of primary failures repairs) and is reflected by an increase in the system operation better quality [3].

In order to build a mathematical model of secondary failures repair costs, connected with a change of the repair technology, the following denotations have been accepted:

M - boundary level of expenditure on a change of repair technology for primary failures caused by external factors (constant),
N - current level of expenditure on a change of repair technology for primary failures (variable),
$\overline{n_{uw}}$ - mean number of secondary failures generated by primary failures (number of failures is a random variable with Poisson distribution with parameter λ),
n - mean time of a secondary filure repair (repair time is a random variable with defined distribution),
KC - total cost of secondary failures repairs in a finite time interval,
KS - mean cost of secondary failures repairs in afinite time interval,
α - coefficient resulting from existence of a benefit and a disadvantage from the scale of expenditure on a change of primary failure reapir technology,
β - coefficient defining the degree of boundary expenditure utilization for a change of technology of primary failures repairs, in scale (1, 2).

For the accepted denotations, it is necessary to define the dependence of the number of secondary failures on the expenditure on a change of technology of primary failure repairs, from dependence:

$$n_{uw}\left(N\right) = \beta \overline{n_{uw}} \ . \tag{7}$$

The dependence of duration time of secondary failure repairs on expenditure on a change of primary failure technology repairs:

$$T_{uw}\left(N, \overline{T_{uw}}\right) = \beta^2 \overline{T_{uw}} \ . \tag{8}$$

Dependence of the total secondary failure repair costs (in a finitetime interval) on expenditure on a change of primary failure repair technology:

$$KC\left(N, n_{uw}, T_{uw}\right) = \alpha N^2 + N + n_{uw} T_{uw} \, . \tag{9}$$

Dependence of the mean cost (in a finite time interval) on expenditure on a change of primary failure repair technology:

$$KS\left(KC, N, n_{uw}\right) = \frac{KC}{n_{uw}} \cdot \tag{10}$$

Next, substituting expresssions described by dependencies 7 and 8 to dependencies 9 and 10, we receive, respectively:

$$KC\left(N\right)=N+\alpha N^2+\beta^3\overline{n_{uw}}\overline{T_{uw}}. \tag{11}$$

Thus, for the mean cost (in a finite time interval) we receive the general form:

$$KS\left(N\right)=\frac{KC}{n_{uw}}=\frac{1}{n_{uw}}\left(N+\alpha N^2+\beta^3\overline{n_{uw}}\overline{T_{uw}}\right). \tag{12}$$

Thus, dependencies 11 and 12 are a mathematical model of the total and mean costs connected with a change of primary failure repair technology [3].

6. Model of transport means operation and maintenance process assessment considering the influence of primary and secondary failures on the system operation efficiency

On the basis of the above study, a semi-Markov model of transport means operation process has been built. This model provides basis for an assessment of the influence of performed repairs of the transport means particular subsystems on the system operation efficiency.

In order to provide a possibility to carry out simulation tests aiming at evaluation of profits connected with the mean number of secondary failures falling on one primary failure, a program has been developed in a computing system language R [2]. This environment has been chosen because it provides functions for generation of random values from different probability distributions. In the model described in the previous chapter, generators of random variables are used with gamma and logarithmic-normal distributions. Another reason for choosing environment R is that it facilitates making a ststistic analysis of the generated simulation courses, including tests of hypothesis of consistence with given types of distributions as well as parametric tests of the scale parameters values of particular distributions.

The simulation program takes input data for calculation from text files containing general parameters such as:

- number of technical objects,
- number of the process states,
- number of events to be generaed,
- number of secondary failures falling on one primary failure.

Parameters which describe precisely the semi-Markov process such as: types and parameters of distributions for generated times of being in the process states, matrix of changes of states of the Markov chain entered into the semi-Markov process, the vector of profits for a time unit. It was assumed that the time of being in state 1 is described by gamma distribution and in states 2 and 3 by logarithmic-normal distributions.

The simulation experiment can be planned for one technical object or for a group of them. The results generated during simulation are saved in a text file, in a chronological order of events, no matter whether the course applies to a single object or to a group of them. Each verse contains four values, which are:

- Tmod the model time,
- technical object number,
- state in which the technical object is,
- time (time of being in the state).

Also a file with computed statistic data enabling verification of correctness and stability of the simlation program operation, has been created. The file contains characteristics of the simulation experiment computed within the program:

- number of entries to the states,
- boundary probabilities of the entered Markov chain,
- boundary probabilities of the semi-Markov process,

- mean and standard deflections of being in states,
- results of Kołomogorow-Smirnow tests of consistence with the assumed types of distributions,
- mean profit for a time unit calcualted as the scalar product of boundary vector of probabilities for the semi-Markov process and the vector of profit for a time unit.

The below presented data and charts are results of a seris of simulation experiments which assume that the number of secondary failures decreases in the successive experiments (change with step1). This is reflected by a decreasing summary time of being in state 3. The mean time of being in state 1 increases by a value connected with the time of being in state 2, though with decreasing efficiency. This means that the efforts made to reduce the mean number of secondary failures falling on one primary failure are connected with increasing costs or in other words are less and less effective [3].

The relation between the change of secondary failures number and the increase in the mean time of being in state 1 is given in Fig. 2 (value of multiplier of the mean time of being in state 3).

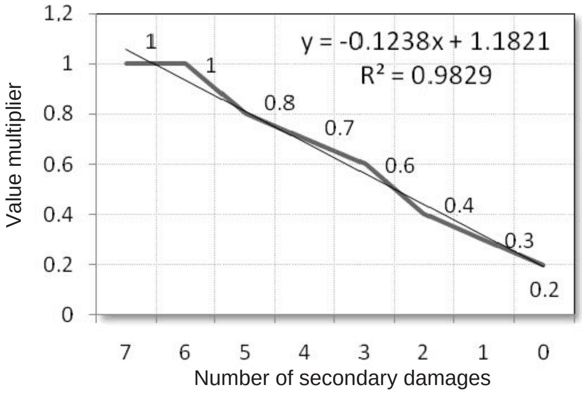

Fig. 2 The value of multiplier reducing rise of the mean time of being in state 1

Table 1. contains characteristics of particular simulation experiments. Whereas, in Fig. 3, an evolution of a single mean profit in dependence on the number of secondary failures, has been presented.

Tab. 1. Results of mileages for different values of secondary failure numbers

				Experiment				
Mileage	LUWt	Parameters in state 1	Mean in state 1	1	2	3	4	5
1	8	7.00	70.00	905.39	906.39	907.38	905.74	905.95
2	7	7.28	72.77	910.39	908.63	909.45	906.71	910.09
3	6	7.55	75.54	910.21	910.96	911.63	911.15	910.99
4	5	7.78	77.76	912.18	912.67	912.69	912.39	911.98
5	4	7.97	79.70	912.48	912.18	913.54	912.51	912.36
6	3	8.14	81.36	913.54	911.84	913.01	910.64	912.80
7	2	8.25	82.47	909.15	908.07	909.40	908.70	909.88
8	1	8.33	83.30	900.52	900.91	900.53	902.23	900.35
9	0	8.39	83.85	874.37	878.14	874.65	878.01	876.04

For the purpose of depicting the discussed experiment transparency, a chart containing a few series of data has been presented in Fig. 3.

7. Conclusion

The above presented, thee-state model of the operation and maintenance process is a semi-Markov process, taking into account the interrelation of technical objects failures occurring during operation, with distinction between primary and secondary failures.

The static analysis of simulation tests, taking into consideration different types of probability

The static analysis of simulation tests, taking into consideration different types of probability distributions for times of being in the process states and their different parameters, obtained from ‘Kołmogorov-Smirnov’ static tests of consistence with the distribution type and ‘z’ test of positional parameters values, proved correctness of the model.

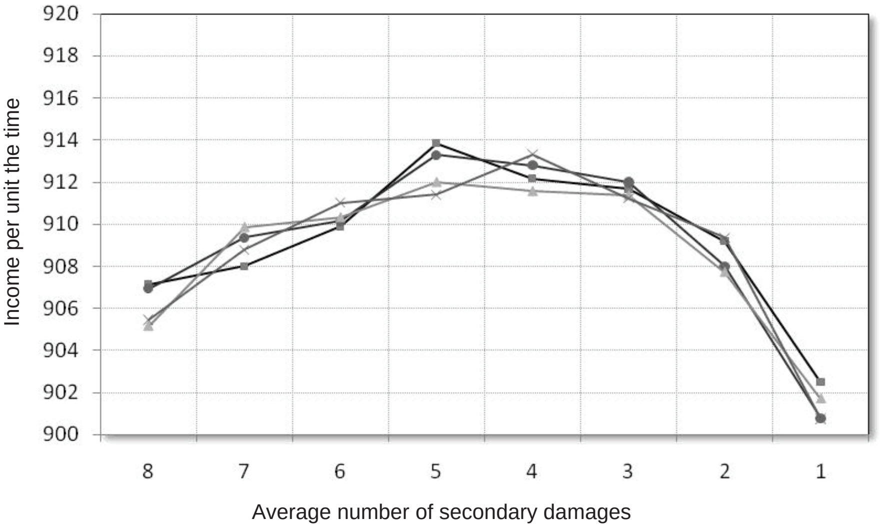

Fig. 3. Evolution of profit for a decreasing number of secondary failures

Realization of the operation and maintenance process (containing chronological succession of events in the process) makes it possible to claim correctness .of the discussed approach whose purpose is to define optimal operation leading to maximization of the profit from operation and maintenance through changing the technology of primary failures, directly affecting the studied system operation efficiency.

References

[1] Begg, D., Fisher, S., Dornbusch, R., *Mikroekonomia*, Polskie Wydawnictwo Ekonomiczne, Warszawa 2003.
[2] http://www.r-project.org – (The R Project for Statistical Computing)
[3] Muślewski, Ł., *Podstawy efektywności działania systemów transportowych*, ITeE, Radom 2010.
[4] Muślewski, Ł, Wdzięczny, A., *Qualitative Aspect of Means of Transport Failure Causes*, Polish Journal of Environmental Studies, Vol. 18, No. 2A, Hard Olsztyn 2009.
[5] Muślewski, Ł., Wdzięczny, A., *Damage rate as a reliability characteristics having significant influence on the operational quality of the technical objects being operated and maintained in the transport systems*, Journal of KONES Powertrain and Transport, Vol. 15, No. 4, Warsaw 2008.
[6] Woropay, M., Migawa, K., Szumiński, H., Wdzięczny, A., *Analiza skuteczności realizowanych napraw podzespołów autobusów eksploatowanych w systemie komunikacji miejskiej*, Materiały konferencyjne, Międzynarodowa Konferencja Naukowa, Transport XXI Wieku, Warszawa 2004.
[7] Woropay, M., Wdzięczny, A., *Analysis and evaluation of risk in a transport system*, Journal of KONES, Vol. 13, No. 2, Warszawa – Nałęczów 2006.
[8] Woropay, M., Wdzięczny, A., *Analysis and evaluation of the influence of the bus braking subsystem damages on origination of damagers in a sociotechnical system*, Journal of KONBiN, The 4th International Conference on Safety and Reliability KONBiN, Vol. 1, Kraków 2006.
[9] Woropay, M., Wdzięczny, A., Bojar, P., Szubartowski, M., *Metoda oceny wpływu skuteczności realizowanych napraw na niezawodność i bezpieczeństwo działania systemów transportu miejskiego*, ITeE, Radom 2008.