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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

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Abstract

This paper presents theoretical basis for evaluation of the transport system operation quality. A general evaluation model was built, and further part of the paper is to consider the theme of damageability of the means of transport, as a reliability feature, constituting one of the most important criterion to evaluate the transport system operation. Based on the analysed references in question as well as on the results of our own research it has been found that the damages to the means of transport, being utilised within the transport systems, are a result of interaction of various forcing factors. 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 secondary 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, which directly affects reliability of the means of transport and consequently the operation quality of the transport systems in which they are being operated and maintained. Based on the analysis of the investigation results it has been found that the primary damages are independent on one another and they occur randomly. The secondary 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 secondary damage.

Keywords: *transport system, reliability, efficiency, maintenance, failures*

1. 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 sociotechnical 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.

2. Systems operation quality

The method to evaluate the operation quality of the complex transport system presented in this chapter has been elaborated with the use of the classical quality theory elements presented by

J.M. Juran, F.M. Gryna, K. Ishikawa, E.W. Deming, R. Kolman and by others as well, and with taking into consideration the TQM rules and ISO standards. Moreover, the paper presents also a complex method, describing the evaluation process of the operation quality of the systems, starting from identifying them inclusive of their decomposition, determining criteria and sub-criteria adopted to evaluate the respective system elements and setting the significant features and on such basis building the resultant model to evaluate the system and determining its operation quality at the given moment t with the possibility to compare it at the optional time moments. All the considerations have been performed as strictly connected with widely understood system theory, the general grounds of which are presented in the preceding chapter, and especially with the general conception of the system state evaluation.

This point includes description of the rules, based on which a method to evaluate the quality of the transport system operation has been formulated. A general evaluation scheme is shown in the Fig. 1.

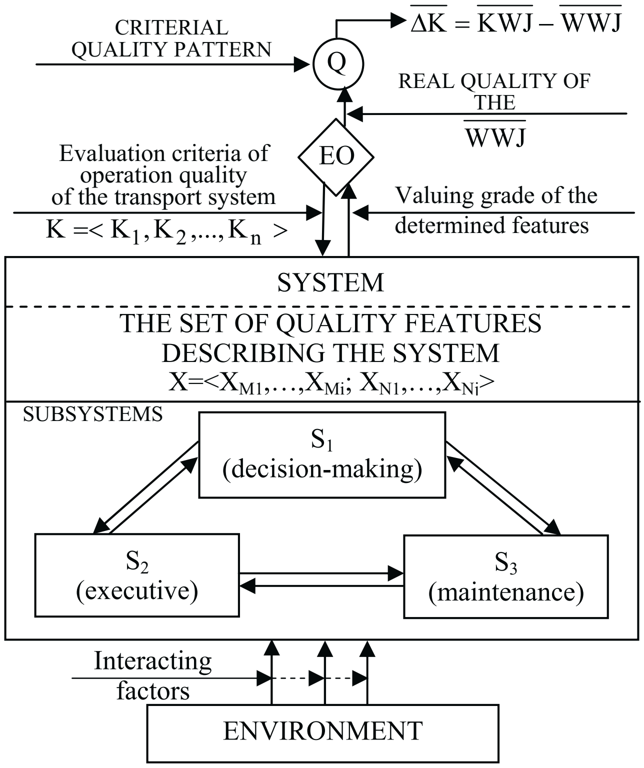

Fig. 1. Scheme of evaluating operation quality of the transport systems

As it can be seen in the Fig. 1, an external observer - EO determines the criteria set to evaluate quality of the system operation K. Afterwards he identifies the investigation object, and on this basis he sets the set of the features - X describing the system from the point of view of its operation quality. The Tab. 1 shows consecutive stages in the process of identifying the set of significant features, the setting of which is the basis for evaluating of the system[7, 17].

Having in mind that all the considerations in this paper deal with the evaluation of the operation quality of the transport systems of <H-M-E> type, according to the general scheme presented in the Tab. 1, the metacriterion - M is the operation quality of the transport system, while the system elements E create a three-element set, composed of: e1-human, e2-machine and e3-environment.

On the basis of analysing the relevant literature and our own investigations it has been defined that: the operation quality of the system is a set of the system features expressed by means of their numeral values at a given moment t, determining the level of accomplishing the required conditions. The notion of quality defined that way makes it different from the definitions being applied up to know [3-5], because it has been unambiguously stated that quality is measurable and its valuation is presented as numerical values. Such an approach makes it possible, after prior determination of the quality requirements as to the operation of the system under investigation, its individual elements and the processes being carried out within it, to determine and express by means of the numerical values its operation quality at any moment t.

Tab. 1. Realisation stages of the process to determine the resultant model of evaluating of the transport system

External observer	EO				Evaluator
Meta-criteria	M_1	M_2	…	M_n	Point of view
Study object	S (system)				System identifying
System elements	E				
	e_1	e_2	…	e_n	
Criteria	K $<K_1,K_2,\dots,K_n>$				Criteria identifying
Sub-criteria	$k_1(e_1)$	$k_2(e_2)$	…	$k_n(e_n)$	
Features	$X_1,\dots$ $\dots,X_{k1}$	$X_{k1+1},\dots,X_{k2}$	…	$X_{kn-r},..$ $..X_{kn-1},$ $X_{kn=p}$	Features identifying
Evaluation model	$X=<X_1,X_2,\dots,X_p>$				Resultant form

In this paper, the criterion term has been defined as one of the significant conditions, imposed on the feature value, which describes the quality of the analysis subject at a given moment t. A feature is a property or quality of the analysis subject. We call a property such a feature which is common for all the subjects which is expressed as a physical quantity, whereas a quality we call such a feature which lets us distinguish some objects which do not have these features [11].

3. The model to evaluate operation quality of the transport systems

The system model is such an arrangement that may be conceived or materially realized, which by representing or reproducing the investigation object is capable of replacing it in such a way that when it is being investigated it provides us with new information on this object [14]. However, it is to be taken into account that the model is always a simplification, idealization of a process or a system. The model should perform such functions which are to catch significant variable phenomena and processes under investigation while omitting the others. Dividing the variables into significant and insignificant ones depends mainly on the investigator's perception, state of his knowledge, measurement and calculation facilities and the adopted method, tools and investigating techniques.

In order to set valuation of the operation quality of the system under investigation, it is needed to determine such a set of significant features of the quality $Z = X_i$, $i = 1,2,\dots,p$, which is divided into n - separable subsets $Z_1,Z_2,\dots,Z_n$, meeting the following dependences:

$$Z_i \cap Z_j = \emptyset \text{ for } i \neq j,$$

$$Z(t) = Z_1(t) \cup Z_2(t) \cup \dots \cup Z_n(t). \tag{1}$$

Each of the nth subsets Z_i, where $i=1,2,\dots,n$, is a set of features describing the operation quality of the individual elements of the system. The number of the elements of the system and the features describing it depends on its kind, complexity and characteristics.

Based on our own investigations [19] a general model to evaluate operation quality of the complex transport systems has been built:

$$\begin{aligned}
&Z_1(t)=\{X_1(t),\ldots,X_{k_1}(t)\}\\
&Z_2(t)=\{X_{k_1+1}(t),\ldots,X_{k_2}(t)\}\\
&Z_3(t)=\{X_{k_2+1}(t),\ldots,X_{k_3}(t)\}\\
&\ldots\\
&Z_n(t)=\{X_{k_n-r}(t),\ldots,X_{k_n-1}(t),X_{k_n}(t)\},
\end{aligned}\tag{2}$$

where:
$k_n = p$,
$n \le p$,
$k, n, r, p \in N$,
Z_i - feature subsets describing operation of the individual elements of the system,
$Z_i = e_i$,
$I = 1,2,\ldots,n$,
$E = \{e_i\}$ - elements of the system,
X_i - set of the features describing comprehensively the quality of the system operation,
$I = 1,2,\ldots,p$,
$I = \{1<\ldots<k_1<k_1+1<\ldots<k_2<k_2+1<\ldots<k_n-r<\ldots<k_n-1<k_n=p\}$.

Having in mind, that the paper deals with evaluating the operation quality of the transport systems of <H-M-E> type, the elements of which are: human (operator) - e_1, machine (technical object) - e_2, environment- e_3, subsequently the resultant model to evaluate its operation quality takes the form which is described with the following dependence [16]:

$$\begin{aligned}
&Z_1(t)=\{X_1(t),\ldots,X_{k_1}(t)\}\\
&Z_2(t)=\{X_{k_1+1}(t),\ldots,X_{k_2}(t)\}\\
&Z_3(t)=\{X_{k_2+1}(t),\ldots,X_{k_3}(t)\},
\end{aligned}\tag{3}$$

where:
$k_3 = p$.

4. Reliability as an example of one of the criterion to evaluate operation quality of the transport systems

Having in mind the method elaborated and the general model to evaluate the transport system operation quality built, it should be emphasised that the evaluation process is mainly dependent on appropriate determination of the evaluation criteria and subcriteria and on determination of the most significant - robust, important, variable and measurable features [13, 18], based on which the fulfilment of the required conditions by the system is verified. On the basis of the investigations performed it was found that among the most significant criteria to evaluate the transport system operation quality, the following items were distinguished: safety, punctuality, time consuming, ergonomic features and reliability [17].

The further part of this paper presents exemplary elaborations regarding evaluation of the means of transport reliability, and particularly their damageability which is an important subcriterion in the entire evaluation of the operation quality of these systems.

A 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.

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 secondary 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.

When applying statistical analysis of the moments in which the damages to the means of transport occur, a difference between theoretical and empiric distribution of the time interval values occurring between these moments (Fig. 2) was found. A significant difference between the theoretical and empiric distribution appears at the beginning of the interval $(0, t_p)$, and then from the moment p it reduces to zero. However, the theoretical function is consistent with the empiric distribution in the interval (t_p, ∞). This discrepancy is caused by so called secondary damages resulting from inappropriate repair quality of the damaged elements which occur within this interval. The investigations performed prove that the secondary damage moments are included within the interval from *0* to *7* days (Fig. 1).

The analysis of the empiric data (length of the time intervals between the damages) indicates that it is reasonable to describe the probability distribution of the correct work times with a reliability function $R(x)$ formulated as follows [1, 9]:

$$R(x) = pe^{-\lambda x} + (1 - p)R_w(t). \tag{4}$$

It is a mixture of an exponential distribution $pe^{-\lambda x}$ (of unknown parameters value $(p\lambda)$ with a reliability function $R_w(t)$. Estimation of the distribution parameters $(p\lambda)$ with the reliability function described with the relation (4) is a complex problem.

Assuming that for unknown distribution (of the correct work times) gathered within a limited time interval $(0, t_p)$ it is possible to assess the values of the parameters p and λ. then for high values t it is assumed that: $R(t) \approx p^*exp(-\lambda t)$. Then by applying a method of linear regression (in semi-logarithmic graph) it is possible to evaluate the values of the parameters p and λ for various random samples cut off from the bottom. A standard regression error - $S(i)$ is calculated for each such approximation, where i stands for an index of a day from which the data are analysed. The analysis of $S(i)$ depending on i value indicates that there is a minimum $s(i)$ for various i, mostly for $i = 5, 6, 7,..., 12$.

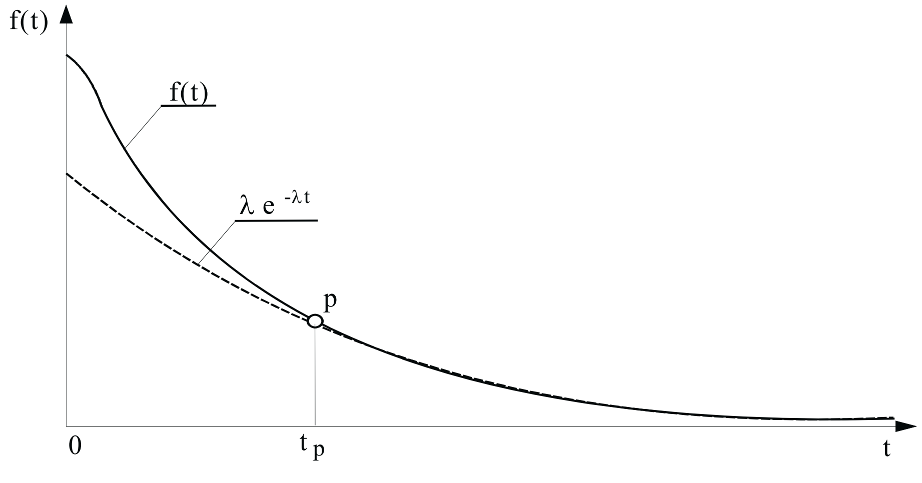

Fig. 2. Changes of the exponential and real functions in the time t

The real function flow may be described with a mixture of a probability distribution of the density $g(t)$ with an exponential distribution.

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

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

$Y_i(n)$ denotes the 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.

From the Grigelionis' theorem it is known that for $n \to \infty$ the random variable $X(n)$ has exponential distribution [1].

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

$$f(t) = \alpha \cdot g(t) + (1-\alpha)e^{-\lambda t} \ \text{for} \ f(t) \geq 0 \tag{5}$$

It is a mixture of the probability distribution of the density $g(t)$ with the exponential distribution of the density formulated with the following relation (6):

$$g_1(t) = \lambda \cdot e^{-\lambda t}. \tag{6}$$

The estimation of the parameter α and λ of the density (5) is based on the assumption that the density $g(t)$ takes the values greater than zero which are relatively low within the range from $\langle t_p, \infty \rangle$.

The analysis of the operation and maintenance investigation results regarding the moments in which the damages occur proves that a set of the damages may be divided into the subsets of primary and secondary damages [9].

It results from the fact that the successive moments of the damages to the same subsystems are gathered sequentially after a single damage has occurred.

The Fig. 3 shows an exemplary stream of the damages to a selected subsystem of a mean of transport.

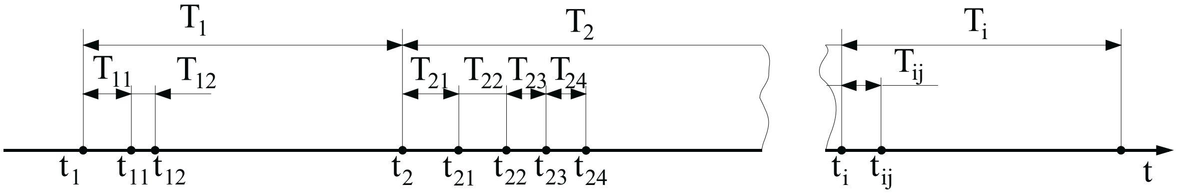

Fig. 3. Time intervals between the primary and secondary damages

t_i - moments in which the primary damages occur,

t_{ij} - moments in which the secondary damages occur,

T_i - time intervals between the moments in which the primary damages occur,

T_{ij} - time intervals between the moments in which the secondary damages occur.

As it can be seen in the Fig. 3, the first of the damages which occurred in the moments t_i, cause the sequences of the successive damages to the same subsystem within short time intervals. These damages are called primary ones.While, the damages that follow them, with finite number of repetitions, and occur in the moments t_{ij}, are called secondary damages.On the basis of the analysis of the investigation results it has been found that, in general, the reason for the secondary damages is inappropriate quality of the repairs of the primary damages, subsystem elements.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 secondary 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 secondary damage.

It means that the secondary 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 secondary 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 and as a consequence due to the reduced failure of the utilized transport means and increase in the operation quality level of the transport systems.

As it can be seen in the below diagram, the repair faults represent one of the most important reasons for the occurred damages to the individual subsystems. Comparison of the significant reasons for these damages is shown in the Fig. 4.

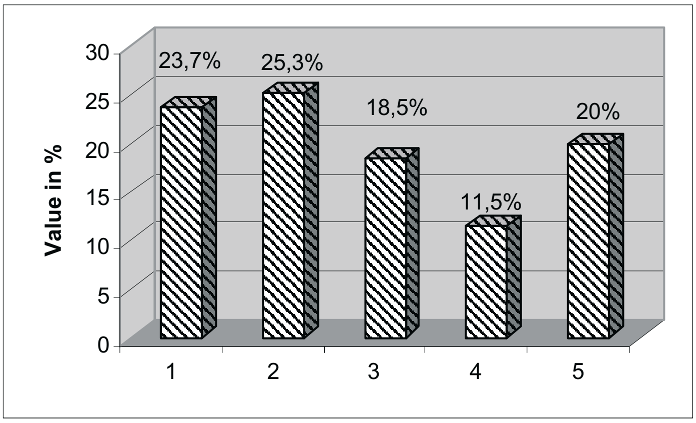

Fig. 4. Occurrence frequency of the reasons for the damages to the system elements; 1 - repair faults, 2 - use faults, 3 - influence of the environment, 4 - damages to the co-working elements, 5 - others

The analysis of the operation and maintenance investigation results prove that reduction of the number of the secondary damages is an essential problem, the solution of which makes it possible to improve especially the operation reliability level of the systems in which they are being operated and maintained.

In order to classify the damages as primary and secondary ones, the following features were evaluated:

- Regarding the distance travelled or transmission (in km, kW/h or m^3) between the consecutive damages to the subsystems, as per the relationships (8) and (9), where:

L_u - stands for the summarised number of the damages to the system,
L_{um} - stands for the number of the damages of the *j*-th subsystem - element,
P_c - stands for the total distance travelled or energy transmission during the investigations,
$L_{śrj}$ - stands for the average transmission between two consecutive damages of the investigated *j-th* subsystem, described with the relationship (7):

$$L_{śrj} = \frac{P_c}{L_{uj}} \quad j = 1,2,...,m, \tag{7}$$

- previous damage to the *j*-the subsystem was a primary one L_{upj} with fulfilling the relationship (8):

$$L_{upj} = L_{ij} \geq L_{śrj} - s_j,\ j=1,2,...,m, \tag{8}$$

- previous damage to the *j*-the subsystem was secondary L_{uwj} with fulfilling the relationship (9):

$$L_{uwj} = L_{ij} < L_{śrj} - s_j,\ j=1,2,...,m, \tag{9}$$

where:

$L_{śrj}$-s_j - value describing the threshold between the primary and secondary damages [*km*, *kW/h or m³*]

- Regarding the measurement of the time s t_{kr} determined on the basis of the average time of correct operation between the consecutive damages to the specific subsystem - element.

Basing on the analysis of the operation and maintenance investigation results it was assumed that the time intervals of the correct operation between the consecutive damages to the respective subsystem may be expressed by means of an exponential distribution. While the condition of the critical time t_{kr} was set on the basis of the dependences described below [1, 6, 8, 20]:

$$F(t_{kr}) = 1 - e^{-at_{kr}}, \tag{10}$$

$$F(t_{kr}) = 1 - \alpha, \tag{11}$$

$$f(t_{kr}) = ae^{-at_{kr}}. \tag{12}$$

After comparing the equations (11) and (12) the following relationship was achieved (13):

$$1 - e^{-at_{kr}} = 1 - \alpha. \tag{13}$$

Thus:

$$\alpha = e^{-at_{kr}}. \tag{14}$$

By logarithming both sides of the equation the relationship (15) was achieved:

$$-\ln\alpha = at_{kr}. \tag{15}$$

After transforming the relationships (10-15) the critical area of the exponential distribution was obtained, which is expressed with the relationship (16).

$$t_{kr} = -\frac{1}{\hat{a}}\ln\alpha, \tag{16}$$

where:

α - significance level,

$\hat{a} = \frac{1}{\bar{t}}$ - estimator of a parameter with the moment method,

$\bar{t}$ - average value of the time interval of the correct operation between he damages to the subsystem.

In order to determine the value of the efficiency factor of the performed repairs the following relationships and dependences were adopted.

N(t) - summarized number of the repairs of the technical object under investigation up to the moment *t*, is described with the relationship (17):

$$N(t) = \sum_j N_j(t),\ j = 1,2,...,m. \tag{17}$$

$N_j(t)$ - number of the repairs of the *j*-th subsystem up to the moment *t*, was described with the relationship (18):

$$N_j(t) = N_j^S(t) + N_j^N(t),\ j = 1,2,...,m, \tag{18}$$

where:

$N_j^S(t)$ - number of effective repairs of the *j*-th subsystem up to the moment *t*,

$N_j^N(t)$ - number of ineffective repairs of the *j*-th subsystem up to the moment *t*

The values $N_j^S(t)$ and $N_j^N(t)$ were determined on the basis of the following relationship:

$L_{śrj}(t)$ - average transmission, travelled distance or transmission between the repairs of the *j*-the subsystem, described with the dependence (19):

$$L_{\acute{s}rj}(t)=\frac{L_{1j}(t)+L_{2j}(t)+...+L_{nj}(t)}{N_j(t)}=\frac{1}{N_j(t)}\sum_{i=1}^{n}L_{ij}(t), \qquad (19)$$

for i = 1,2,...,n, j = 1,2,...,m
where:
$L_{ij}(t)$ - the travelled distance or transmission between the consecutive repairs of the *j*-th subsystem up to the moment *t,*
$N_j(t)$ - number of the repairs of the *j*-th subsystem up to the moment *t.*

The value of the *efficiency factor* of the performed repairs of the *j*-th subsystem - element is described with the relationship (20) [2,10,12,15]:

$$WS_j=\frac{N_j(t)-N_j^{N}(t)}{N_j(t)}=\frac{N_j^{S}(t)}{N_j(t)},\ j = 1,2,...,m. \qquad (20)$$

The value of this factor may be expressed with the relationship (21):

$$WS_j=\frac{N_j^{S}}{N_j}*100[\%],\ ,\ j = 1,2,...,m. \qquad (21)$$

On the basis of the operation and maintenance investigation results, performed in an urban bus transport system, the Fig. 5 shows the values of the repair effectiveness index, depending on the percentage reduction of the secondary damages number, being a consequence of an improved quality of the repairs of its chosen subsystems.

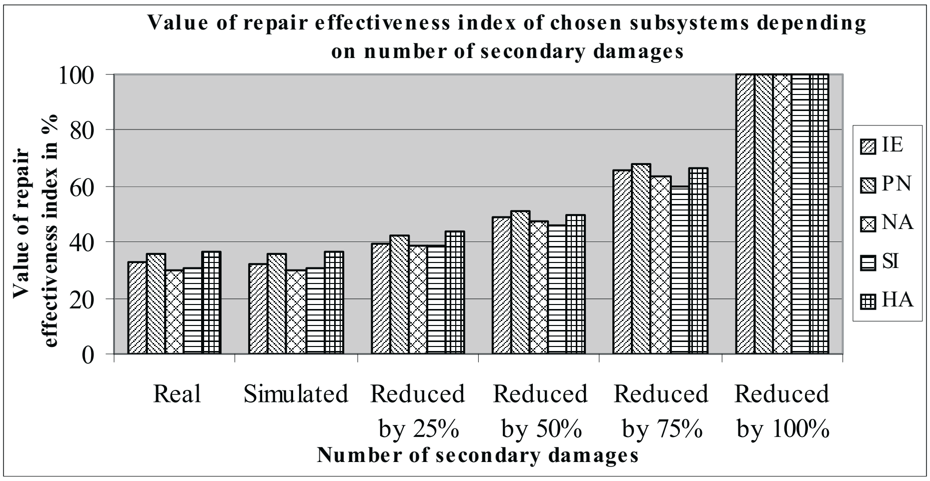

Fig. 5. Change of the value of repair effectiveness index depending on the percentage reduction of the number of secondary damages to the chosen bus subsystems

As it can be seen in the Fig. 5, elimination of the secondary damages in 100% causes an increase in the value of the repair effectiveness index up to one. However elimination of the secondary damages number by *25%, 50% and 75%* causes an increase in the effectiveness index value, which of course is reflected by increased reliability of the investigated means of transport operation and maintenance system.

5. Summary

On the basis of the investigations performed it may be concluded that a secondary damage to particular elements or subsystems, resulting from ineffective repairs, should be eliminated in the servicing process, thus increasing operation reliability of the means of transport being operated and maintained.

The operation and maintenance investigation results prove that carrying out the actions aimed at improvement of the repair effectiveness is reasonable and that they should be considered as being significant and indispensable to increase the quality level of the transport systems operation and particularly: reliability, safety and effectiveness of the operation.

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