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ANALYSIS OF OPERATION EFFICIENCY OF SELECTED TRANSPORT SYSTEMS

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Abstract

This study deals with the problems connected with evaluation of technical systems efficiency of particular transport systems. The main goal of such a system operation is its effective functioning, through rational control of its particular activities and subsequent processes. A literature analysis of the definition of the efficiency term has been made. A real transport system has been accepted to be the research object. The system belongs to the group of sociotechnical systems in which evaluation of its operation efficiency depends on performance of operators, transport means and the impact of environmental factors. Criteria and methods of operation efficiency evaluation have been determined in this study as well as assessment indexes for transport systems. It has been shown that evaluation of a repair efficiency has a large influence on the efficiency of the whole system operation, especially the influence of secondary failure repairs, on the values of particular efficiency indexes. A semi-markov model of operation and maintenance of transport means used in the research object has been developed. This model provides the basis for evaluation of the influence of the processes involved in preparing transport means for service on the system operation efficiency. Moreover, the research also describes how to verify the developed model and present its simulation tests. The study is summarized with conclusions formulated based on the evaluation of the influence of the operation and maintenance processes on the investigated transport system operation efficiency.

Keywords: *transport system, efficiency, operation and maintenance process, semi-markov process, simulation tests*

1. Introduction

The problem connected with evaluation of technical system operation efficiency is a complex one. Literature does not provide any explicit and unequivocal solutions. A review of literature available on the subject of technical systems efficiency reveals different approaches to the analysed issue, which is due to complexity and multi-dimensionality of the analysed research objects. Thus, one can find many different, definitions of efficiency, depending on the scientific discipline, specialization or the investigated object type.

In general, the term ‚efficiency‘ is quite complex and needs to be considered in terms of economy, management, investment effectiveness, technology (in economic disciplines it is understood as evaluation of phenomena, events, and processes occurring in a given sector of economy or social-economic activities such as trade, industry, farming, labour, consumption, shaping, etc.), combat efficiency (the army), educational efficiency, (field of pedagogy), technical-economic efficiency (engineering) [3, 4, 6, 7] as well as dynamic and financial efficiency [15].

Literally, a system is efficient if it provides an expected effect. However, the above statement does not include the element of evaluation, whereas the outcomes can be positive or negative. Positive effects are referred to as benefits whereas the negative ones as outlays – costs or losses. In different times of operation, the relations between benefits and outlays may differ to be eventually determined after performance of a given task. Obviously, the case when benefits prevail over the costs will be the most appreciated [13, 14, 16].

Therefore, we treat efficiency as the relation between benefits (economically viewed as gain or profit) and outlays reflected by costs or losses. It assumes the form of a difference or quotient of these quantities. In certain cases, some of these quantities can assume constant values, which are treated as base ones.

According to the author of work [9], efficiency is an important characteristic of the operation process quality. In analysing, the process of maintenance and operation of a given transport means the identified efficiency measures are expressed by the relations between the achieved effect and the duration time of the operation process or its particular periods. They can also be determined from the relations between intensity of an object operation potential loss during performance of a task and intensity of its potential recovery.

2. General characteristics of the research object

In this study, the research object is a real system of urban rail transport. It is one of the public transport subsystems of an agglomeration with the population of 400 thousand people. Urban rail infrastructure is based on a tramway track gauge equal to 1000 mm. The infrastructure consists of: tramway lines, tramway depot, (functioning as the so called logistic subsystem), tram loops (reversing and technical), stops, bridge rails and viaducts.

The analysed system provides transport services over 11 lines (including one seasonal), total length of which is over 120 km, whereas the length of a single rail is approximately 90 km, and the length of trackage over 40 km. One and two – wagon trams are used as well as modern multiple-wagon trams and historic sets on the seasonal line. Characteristics and size of the rolling stock are included in table 1.

Tab. 1. Characteristics and size of the rolling stock [1, 2, 8]

Series	Number	Number of wagons	Number of seats	Low floor percentage	Producer
805 Nm	2	1	20	0%	Konstal
805 Na	110	1	20	0%	Konstal
122 NaB *Swing*	12	5	40	100%	Pesa
122 N *Tramicus*	2	5	63	100%	Pesa

Appropriate operation quality of such a system is of key importance as it provides the inhabitants of the agglomeration with important transport services. Therefore, maintenance services and transport services should be carried out on time, safely, efficiently and economically.

3. Research subject

The research subject includes selected issues connected with operation efficiency of the research object. This analysis mostly covers the problems of the influence of transport means repairs on the system operation efficiency. The analysis of tests results and literature review show that evaluation of a repair efficiency has a large influence on the efficiency of the whole system operation, especially the influence of secondary failure repairs, on the values of particular efficiency indexes [23].

Factors involved in maintenance and operation-affecting components of technical objects cause negative changes of their significant features leading to their damage.

These forcing factors include those, which are caused by improper behaviour of humans, and those, which are related to the environmental impact. Failures are referred to as events, which largely impair efficiency, safety and reliability of a vehicle operation.

Based on tests performed at the times of failure occurrences it was found that the set of failures could be divided into subsets of *primary* and *secondary (repeatable)* failures. It was proved [22] that secondary failures occur because of inappropriately performed repairs of primary failures. Primary failures are not dependent on each other and occur randomly, whereas secondary failures are dependent on each other as they are conditioned by occurrence of earlier failures and an inappropriate performance of a successive secondary repair. A certain number of failures though result from a natural wear of machine components, whereas, the highest number of secondary failures is the effect of incorrect repair of previous failures.

This is the mechanism of occurrence of the so-called repeatable failures in a short period, which are most frequently caused by inappropriate organization of repairs, poor skills of mechanics, and mistakes connected with pre-and post-repair diagnosing, etc.

The analysis of tests proves that reduction of the number of secondary failures is the main problem whose solution would provide the possibility to control efficiency and reliability of transport means. Experimental tests performed in a real system of transport means operation included an analysis of time periods between particular failures as well as times of their occurrence and the basic statistical parameters such as: the number of primary failures (L_{up}), the number of secondary failures (L_{uw}) have been determined on the basis of literature studies [19,21,22].

4. Estimation of secondary repair costs

Knowledge of available technologies and costs connected with using technical equipment of repair stations allows estimating the lowest costs necessary to obtain reduction in secondary failures and the mean time of repair.

Using $\overline{T_{up}}$ for denotation of the mean time of a primary failure repair, $\overline{T_{uw}}$ for denotation of the mean time of secondary failure repair and $\overline{n_{uw}}$ for the number of secondary failures generated by one primary failure, it is possible to present time dependencies, characterizing the repairs of primary and secondary failures, as in figure 1.

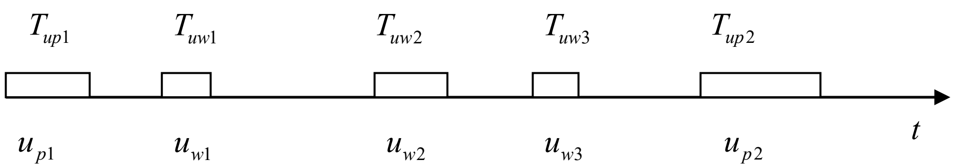

Fig. 1. Time sequences of primary and secondary failures with their duration times

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

$$T = \overline{n_{uw}} \cdot \overline{T_{uw}}, \tag{1}$$

where: T is used for denotation of the total time of secondary failure repairs.

Analysing benefits from the scale of outlays it can be said that a rising expenditure efficiency occurs when long-term average costs fall along with an increase in expenditures. Constant expenditure efficiency occurs when long-term average costs remain constant and expenditures increase. Falling expenditure efficiency occurs when long-term average costs rise along with an increase in expenditure. The dependence defining whether, for established prices of factors involved in operation and maintenance, unit costs rise or fall with an increase in expenditure is affected by technology, which is used, and quality of the repairs.

It is assumed that the curve of costs connected with secondary repair performance is U shaped. This means that for a significant increase in costs connected with a change in technology to be used for primary failure repair, a decrease in the repair efficiency level can be observed. Thus, in this case the phenomenon of diseconomies of scale is observed.

In connection with the above, it was found that an increase in expenditures of primary failure repairs causes reduction in the number of secondary failures and the time of their duration. It decreases the repair costs of secondary failures (despite additional costs connected with primary failures repair technology change) and it is reflected by an increase in the system operation efficiency and quality [10, 12].

It was assumed [11, 12], that dependence (2) describes total costs, whereas dependence (3) average costs connected with changing technology for primary failures repair.

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

For average costs (in a finite period), we will have:

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

where:

N – current level of costs connected with a change of technology to be used for repair of primary failures (variable),

$\overline{n_{uw}}$ – average number of secondary failures generated due to primary failure (number of failures is a random variable with Poisson distribution with z parameter λ),

$\overline{T_{uw}}$ – mean time of a secondary failure repair (time of repair is a random variable with definite distribution),

KC – total cost of secondary failure repair, in a finite time interval,

KS – average cost of secondary failure repairs in a finite time interval,

α – coefficient resulting from economies and diseconomies of scale of expenditure on changing primary failure repair technology,

β – coefficient defining, in scale [0.1], the level of boundary expenditure use for primary failure repair technology change.

A semi-markov model of transport means operation and maintenance (described by graph in Fig. 2), considering the states they are in while performing primary and repeatable failures, has been developed on the basis of the above.

It was assumed that there are 5 states $S=\{1,2,3,4,5\}$. State with no. 1 is a state of intensive use when the engineering object performs a transport task. In state no. 2, a transport means is in the depot where after daily service it is available to be used again and waits for the task to be performed. In third state, the vehicle is diagnosed and be subject to technical survey. State 4 is a renovation state of an object whose damage (repeatable) is an effect of previously occurred failures and quality of the repairs.

It was observed that state 5 occurs more often than state four. It needs to be interpreted in such a way that the quality of a primary failure repair which is exposed to disruptions and difficulties is a significant cause of occurrence of one or more secondary failure in the repaired subsystem or other subsequent subsystems.

The following graph of transport means operation process state changes has been developed based on the carried out tests:

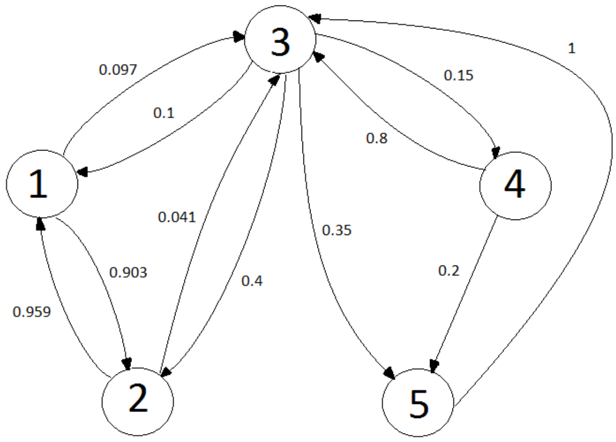

Fig. 2. Graph of semi-Markov process state changes with state change probabilities

Matrix P of state change probabilities for Markov chain has been developed based on a directed graph presented in figure 2.

$$P = \begin{vmatrix} 0 & p_{12} & p_{13} & 0 & 0 \\ p_{21} & 0 & p_{23} & 0 & 0 \\ p_{31} & p_{32} & 0 & p_{34} & p_{35} \\ 0 & 0 & p_{43} & 0 & p_{45} \\ 0 & 0 & p_{53} & 0 & 0 \end{vmatrix}. \tag{4}$$

The first step of determination of boundary probabilities for Markov chain involves developing a system of matrix equations in the form:

$$P^T \cdot \Pi = \Pi, \tag{5}$$

$$\begin{vmatrix} 0 & p_{12} & p_{13} & 0 & 0 \\ p_{21} & 0 & p_{23} & 0 & 0 \\ p_{31} & p_{32} & 0 & p_{34} & p_{35} \\ 0 & 0 & p_{43} & 0 & p_{45} \\ 0 & 0 & p_{53} & 0 & 0 \end{vmatrix} \begin{vmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \\ \pi_5 \end{vmatrix} = \begin{vmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \\ \pi_5 \end{vmatrix}, \tag{6}$$

$$P = \begin{vmatrix} 0 & 0.903 & 0.097 & 0 & 0 \\ 0.959 & 0 & 0.041 & 0 & 0 \\ 0.1 & 0.4 & 0 & 0.15 & 0.35 \\ 0 & 0 & 0.8 & 0 & 0.2 \\ 0 & 0 & 1 & 0 & 0 \end{vmatrix}.$$

Probabilities of state changes have been determined based on analysis of experimental data obtained from the research object, whereas it should be noted that the third rank of the state change matrix determines the average number of failures that occur after a repair of primary failure. This number is expressed by a quotient of probabilities:

$$\overline{l_{uw}} = \frac{p_{35} + p_{34} \cdot p_{45}}{p_{34}}, \tag{7}$$

where:

$\overline{l_{uw}}$ – average number of secondary failures generated by one primary failure,

P_{34}, P_{35}, P_{45} – probabilities of transitions from state 3 to 4, 3 to 5 and 4 to 5.

Based on a system of matrix equations (6), after introduction of standardizing condition (8):

$$\sum_{i \in S} \pi_i = 1 \tag{8}$$

and for definite values of state change probabilities of the modelled process, boundary probability values have been obtained π_i for Markov chain:

$$\pi_1 = 0.4100,$$
$$\pi_2 = 0.4157,$$
$$\pi_3 = 0.1139,$$
$$\pi_4 = 0.0171,$$
$$\pi_5 = 0.0433.$$

Expected values of unconditioned duration times of semi-Markov process states:

$$ET_1 = 6 \text{ [h]},$$
$$ET_2 = 8 \text{ [h]},$$
$$ET_3 = 1 \text{ [h]},$$
$$ET_4 = 3 \text{ [h]},$$
$$ET_5 = 4 \text{ [h]}.$$

Boundary probabilities pi^* of being in the states of the considered X(t) process have been determined semi-Markov process based on the limit theorem. As ergodic properties of semi-Markov process are fully defined by ergodic properties of an entered Markov chain, thus the following dependencies are provided for boundary probabilities of semi-Markov process:

$$p_i^* = \lim_{t \to \infty} p_i(t) = \frac{\pi_i \cdot ET_i}{\sum_{i \in S} \pi_i \cdot ET_i}, \tag{9}$$

where:

$ET_i,\ i \in S$ – expected values of the process state duration times.

Then boundary probabilities p_i^* of being in the modelled semi-Markov, states are described by the following dependencies:

$$p_1^* = \lim_{t \to \infty} p_1(t) = \frac{\pi_1 \cdot ET_1}{\pi_1 \cdot ET_1 + \pi_2 \cdot ET_2 + \pi_3 \cdot ET_3 + \pi_4 \cdot ET_4 + \pi_5 \cdot ET_5},$$

$$p_2^* = \lim_{t \to \infty} p_2(t) = \frac{\pi_2 \cdot ET_2}{\pi_1 \cdot ET_1 + \pi_2 \cdot ET_2 + \pi_3 \cdot ET_3 + \pi_4 \cdot ET_4 + \pi_5 \cdot ET_5},$$

$$p_3^* = \lim_{t\to\infty} p_3(t) = \frac{\pi_3 \cdot ET_3}{\pi_1 \cdot ET_1 + \pi_2 \cdot ET_2 + \pi_3 \cdot ET_3 + \pi_4 \cdot ET_4 + \pi_5 \cdot ET_5}, \tag{10}$$

$$p_4^* = \lim_{t\to\infty} p_4(t) = \frac{\pi_4 \cdot ET_4}{\pi_1 \cdot ET_1 + \pi_2 \cdot ET_2 + \pi_3 \cdot ET_3 + \pi_4 \cdot ET_4 + \pi_5 \cdot ET_5},$$

$$p_5^* = \lim_{t\to\infty} p_5(t) = \frac{\pi_5 \cdot ET_5}{\pi_1 \cdot ET_1 + \pi_2 \cdot ET_2 + \pi_3 \cdot ET_3 + \pi_4 \cdot ET_4 + \pi_5 \cdot ET_5},$$

Boundary probabilities p_i^*: are determined based on defined values π_i and ET_i,

$$p_1^* = 0.4017$$
$$p_2^* = 0.5431$$
$$p_3^* = 0.0186$$
$$p_4^* = 0.0084$$
$$p_5^* = 0.0283$$

The calculated values of semi- Markov process boundary probabilities allow determining profits generated during the process evolution. Accepting profit vector in the form:

$$c=[c_1,c_2,c_3,c_4,c_5], \tag{11}$$

where: values c_i for i=1,2,3,4,5 are values of unit profits (per a time unit of being in state i), it is possible to calculate an average unit profit in a long time period as [17]:

$$K = \sum_{j\in S} c_j P_j . \tag{12}$$

In the next step, it is advisable to build a simulation program with the considered semi-Markov process. In order to perform tests for assessment of profits connected with the average number of secondary failures falling on one primary failure it is proposed to develop such a program in computing system language R [5]. It enables generation of random values from different probability distributions. Our model uses generators of random variables with gamma and logarithmic-normal distributions and environment R that enables a statistical analysis of the generated simulations including consistence hypotheses with distributions of a given type as well as parametric tests with parameter values of particular distributions. The simulation program takes input data for calculations from text files including general parameters such as the number of technical objects, number of the process state, and number of events to be generated, number of secondary failures per one primary failure. The calculation results provide parameters which precisely define Markov process such as: types and parameters of distributions for the generated times of being in the process states, matrix of state changes of Markov chain entered into semi – Markov process or profit vector per one time unit.

5. Conclusions

An initial statistical analysis of the carried out simulation experiments takes into consideration different types of probability distribution for times of being in the process states as well as their different parameters, obtained by means of 'Kolmogorov-Smirnov' statistical consistence tests with the distribution type and test 'z' of the value of position parameters, has shown correctness of both the assumptions and the developed model structure.

The carried out tests have proved that the developed model can be used for analysis a system functioning costs connected with the process of maintenance and operation including a change of primary failure repair technology.

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