

MODELOWANIE PROFILAKTYCZNEGO OBSŁUGIWANIA PARKU SAMOCHODÓW

MODELLING PREVENTIVE MAINTENANCE FOR A VEHICLE FLEET

W referacie przedstawiono metodę utrzymania wymaganej niezawodności parku pojazdów. Założony efekt uzyskano poprzez użycie diagnozowania statystycznego do wskazywania zakresu wymian profilaktycznych. Kryterium wyboru był akceptowalny poziom prawdopodobieństwa uszkodzenia pojazdów podczas realizowania zadań transportowych. Opracowano algorytm wyboru wymienianych składników floty pojazdów. Wykazano, że na poziom niezawodności parku pojazdów można oddziaływać nie tylko poprzez zmianę rzędu kwantyla, ale także poprzez dodawanie odpowiedniej liczby nadmiarowych pojazdów. Dla potwierdzenia wyprowadzonych zależności zastosowano model symulacyjny wymian profilaktycznych.

Słowa kluczowe: obsługa, wymiana profilaktyczna, diagnoza statystyczna

The paper presents a method of means of transport maintenance with a required reliability. Such results are achieved by using statistical diagnosing as a base of preventive replacement of objects in a fleet. The acceptable level of a failure risk while executing transportation tasks has been taken as a criterion. An algorithm for selecting elements for preventive replacement has been developed. It was shown that a level of a fleet reliability can be controlled not only by changing an order of a quantile function but also by adding a number of redundant objects to the fleet. A computer simulation model was used to explicate derived dependencies between a redundancy and a quantile order.

Keywords: maintenance, preventive replacement, statistical diagnosis

1. Introduction

Preventive replacements are used to maintain demanded reliability of vehicles in a transport firm. They enable avoiding failures of individual vehicles in a fleet. However a need for high reliability of fleet of vehicles being used can effects in great amount of elements replaced during preventive actions.

High reliability is achieved in practice by services when specific elements are replaced by new ones. A criterion of selecting elements depends on level of reliability that is expected. In a case of a homogeneous set of vehicles, a range of prophylactic activities depends on a reliability level of the whole fleet and on its reliability structure.

This takes in account redundancy, that enables first off all to replace failed objects enabling of transportation tasks fulfilling. A number of redundant objects depend on the acceptable probability of failure during the task implementation period. In order to minimize the size of redundancy one should, on the one hand, be using objects of high reliability, and also keep their reliability in the operating process at possibly high level, on the other hand.

Instead of known from the literature method of replacing object in a given rate [6], the method of replacing of chosen elements that enables achieving demanded level of the fleet reliability is proposed. This method uses statistical characteristics of the vehicles instead of applying measurable parameters of its elements.

The ability of the object of fulfilling given tasks with demanded probability could be statistically measured by quantile of given order. For this measure, a method of statistical diagnosis was developed. It points out at given moment to a set of elements that should be replaced by new ones to achieve demanded reliability of the whole fleet of vehicles.

2. Preventive replacements

A method that is known from literature and used for defining of a scope and deadlines of preventive replacements is to include the costs of attentive replacements and the costs generated by the occurring failures [1, 5]. As a result of its application, minimum average costs per unit of time related to maintenance of objects in a proper reliability status are achievable. However, in order to benefit from that effect there is a need to replace individual elements in various time intervals, usually uncoordinated with the performance of tasks, which may wipe out advantages effecting from the implemented optimisation. Therefore, a possibility should be considered to make preventive replacements of objects in the assumed time intervals whose scope is defined on the basis of assessment of reliability of the objects and the assumed reliability level of the entire fleet [3]. The fleet maintained in such a way preserves its ability to realise transportation tasks with a given probability.

In case of complex systems, a failure appears whenever an object, which constitutes a series reliability structure with the others, has failed. A repair usually involves a replacement of this object for a brand new one.

Dynamic determination of a scope of preventive replacements could be based on a statistical assessment of present status of objects. The statistical diagnosis is a maintenance methodology in the area of maintaining objects with non-exponential lifetime distribution [3, 4]. It identifies preventive maintenance tasks to realise the inherent reliability of equipment at a minimum expenditure of resources. In order to do that, data is required about a distribution of time to failure and its parameters as well as about its operational use so far (since being new or from the moment of its replacement). The statistical diagnosis uses data gathered during normal utilization of objects. They concern failures, repairs and replacements of objects. Next, the distribution of time

or mileage to failure for each of these elements is determined. It can be done either with the use of data collected in the past or by relying upon experts' opinions at the start.

Statistical inspection can be performed at any moment because it retrieves data gathered in the informational area of the means-of-transport maintenance management system. It could be done either in a constant period of time or during planned service or during current repair. The distribution parameters are modified when either repair or replacement of the element has been done. The actual technical condition of the object is not taken into consideration here as that would require for the object to be excluded from its operational use. Having data, reliability characteristics of elements, updated working time of individual elements, a period for execution of the transportation task, it is possible to define objects that require preventive replacement in order for the project implementation probability not to decline below its assumed value. It can be applied as well to elements as to complex objects.

The procedure statistically predicts failures at part level by calculating a quantile function of residual lifetime instead of the mean residual lifetime to failure. This measure directly relates to predicted work period and the reliability of the system. For any moment t the following condition has to be met:

$$q_p(t) \geq d \quad (1)$$

where: d – tasks implementation period, $q_p(t)$ – quantile of residual lifetime function, order p .

Function $q_p(t)$ shall be defined as follows [2]:

$$q_p(t) = F_i^{-1}(p) = \inf \left\{ x : F_i(x) \geq p \right\} \quad (2)$$

where: $F_i(x)$ – cumulative distribution function of the residual lifetime, $R_i(x)$ – conditional reliability function, and

$$1 - F_i(x) = R_i(x) = \frac{R(t+x)}{R(t)}, \quad x, t \geq 0 \quad (3)$$

A fleet of vehicles in a transport firm could be characterized by reliability and as well as by a reliability structure. Probability of a failure occurring during a task period can be determined in both cases, that is, when the replacements either have or have not been made. Additionally, the assessment may refer to the entire fleet of objects that have been assigned for execution of the transportation tasks.

A preventive replacement of objects is made if the value of function (2), which has been calculated for the entire set of objects, is lower than the duration of the scheduled task planned for that set of objects. In order to select a set of objects to be replaced at given moment, an updated value of the reliability function is calculated including operational time of each and every one of them. Then they are put in order according to the growing value of the quantile of a given order for a distribution of the residual lifetime.

Subsequent objects are assigned for replacement, starting from an object of the lowest quantile value until the quantile of the entire fleet of objects – calculated by having included the replacement of assigned elements for brand new ones – is not less than the duration of the scheduled task (algorithm in Fig. 1). The replacement of objects that have been assigned in this way ensures the assumed probability that the fleet of objects will not fail during implementation of the transport task.

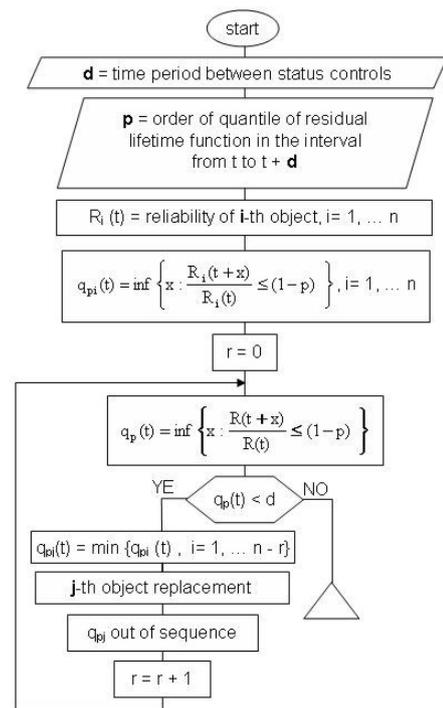


Fig.1. Algorithm for selecting objects for preventive replacement

3. Redundancies in a fleet of objects

Sustaining a high reliability level of technical objects in their operational use process – served by preventive replacements of components being threatened by a failure – can be accompanied by adding redundant objects to the fleet.

If the entire fleet consists of n objects and n objects are essentially required for carrying out transportation tasks, then an assumption can be made that reliability structure of the fleet is in series. This imposes large requirements on reliability of each object, which is often not achievable. Then, in order to keep reliability of the fleet at its required level, redundant objects can be introduced into the fleet. After adding k redundant objects to the fleet its reliability structure can be seen as a threshold structure, in this case “ n out of $n+k$ ”.

The fleet reliability model also depends on the way the redundant objects are operating in. Redundant objects may play a role of the cold (unloaded) reserve, that is, they passively wait for one of the objects to fail, or the hot (loaded) reserve, thus increasing the entire fleet capacity until one of the objects has failed.

In case of the structure “ n out of $n+k$ ” for $k > 1$ in the cold reserve, the analytical description becomes very complex, as there are more reserve objects than in the structure “ n out of $n+1$ ”. This is because that in the fleet, established at the moment τ and consisting of $(n-1)$ objects aged τ and one new object, one of the objects may fail and be replaced by the second reserve object before the moment t .

In case of the fleet with structure of “ n out of $n+k$ ” with the hot reserve, we may use the simpler relation for homogenous objects:

$$R_{(n,n+k)} = \sum_{i=n}^{n+k} \binom{n+k}{i} R^i (1-R)^{n+k-i} \quad (4)$$

Complexity of the analytical description, regardless of simplifying assumptions that have been made (i.e. identical objects, omission of the reliability structure of objects alone), indicates that there is a need for using a computer simulation for issues being considered here.

If k vehicles works as the hot reserve, the system can be treated as “ n out of $n+k$ ” structure and the order p represents demanded level of reliability of the whole fleet. However, in the case of k redundant vehicles working as the cold reserve with n objects presenting a series reliability structure, there is a possibility for calculations new value for the level of reliability, which decreases the reliability demands. The formula is as follows:

$$1 - \alpha_k = \frac{1 - p}{(1 - R)^k \left[\binom{n+k}{n} + \sum_{i=1}^k \binom{n+k}{n+i} \left(\frac{R}{1-R} \right)^i \right]} \quad (5)$$

where: α_k – probability of failure one of n vehicles ($\alpha_0 = p$), p – acceptable probability of system failure, R – reliability of a single vehicle, n – number of vehicles needed for transportation tasks execution, k – number of redundant vehicles.

This new order is greater then that assumed for the whole fleet without redundancy. The relation between orders (p, α_k) is shown in Fig. 2.

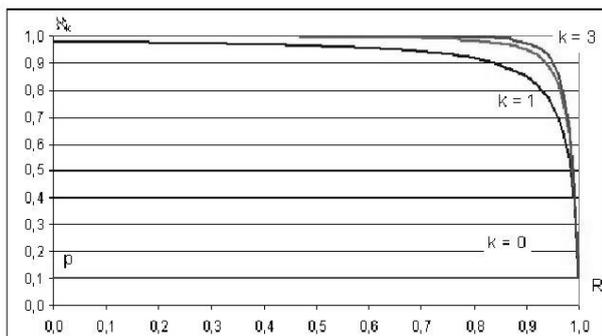


Fig.2. Relation between α_k and R for the given n, k and p

4. Simulation experiments

The above consideration was confirmed with use of a computer simulation. In the model, objects were applied, that were fully replaced at steady intervals of mileage, according to results of statistical diagnosis. The planned process of replacements was combined with random process of failures and repairs. A graph of model states is presented in Fig. 3. The meanings of model states are as follows: *work* – object is working, *statistical diagnosing* – set of objects is selected, *preventive replacement* – selected objects are replaced by new ones, *repair* – failed object is replaced by a new one)

The fleet of n objects was used for execution of tasks in the model. The mileage to failure of a single object was assumed as the Weibull distribution. The acceptable probability of the fleet unavailability was p . The required reliability was maintained by preventive replacements of objects. Statistical diagnosing was done with the period of length d . Three options of the model were applied. In the first n objects was used, that means the fleet without redundancy. Next, $n+1$ objects was used, with one redundant object, and then $n+2$ objects, with two redundant objects.

Parameters of the model were as follows: $n = 50, p = 0.1, d = 3$, and $a = 2.5, b = 50$ as the Weibull distribution parameters.

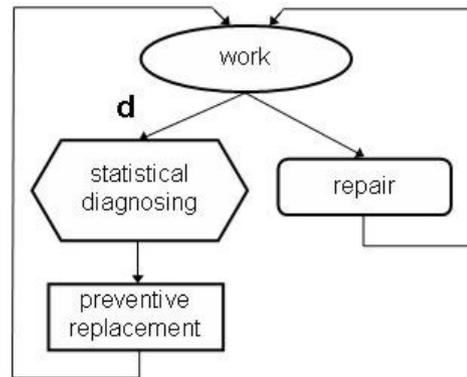


Fig.3. Graph of model states

The range of simulation was $T = 1000$, and experiments were repeated 10 times. As a result of simulation, numbers of replacements and failures of objects and unavailability of the whole fleet were estimated.

In the first step, the number of failures in the system “ n out of n ” without any prophylaxis and then with statistical diagnosing was estimated (Tab.1).

Tab.1. Simulation experiments results for system “ n out of n ”

	Without preventive replacements	With preventive replacements $d = 3$ $p = 0.10$
Number of:		
- preventive replacements	-	10322
- fleet unavailability	1102	34
- object failures	1102	34

The results show that it is possible to achieve demanded reliability with significant decreasing the number of random brakes in work but with a very big number of preventive replacements, as the object reliability was rather low

The reliability of the fleet can be also enlarged by adding redundancy to the system. This decreases the number of preventive replacements in system “ n out of $n+k$ ” as – according to formula (5) – the result is analogical to appropriate increasing the quantile order of the system “ n out of n ”. Such modification of the quantile order can be designated graphically as it is shown in Fig. 4.

The modified orders of quantile calculated with use of formula (5) for systems with $n+1$ and $n+2$ objects are as follows: $\alpha_1 = 0.41, \alpha_2 = 0.66$ (Fig.4). But this result would be valid only for a new system or for a perfect repair after every statistical diagnosing, i.e. whole fleet is replaced by the new one. This condition could be fulfilled if the interval of statistical inspections were long enough. However, such a long interval is useless and practically should be lower than quantile of given order at $t = 0$.

After a number of preventive replacements of objects the fleet consists of objects of different age. This means that an average object is improved by the statistical diagnosing. So the probability of tasks fulfilling by a single vehicle should be calculated for systems “ n out of $n+1$ ” and “ n out of $n+2$ ” separately on the base of experimental data (Tab. 2). Then the modified orders α_k for appropriate systems “ n out of n ” can be calculated with use of formula (5). The empirical values are as follows: $\alpha_1 = 0.40, \alpha_2 = 0.64$. The procedure is presented in Fig. 5.

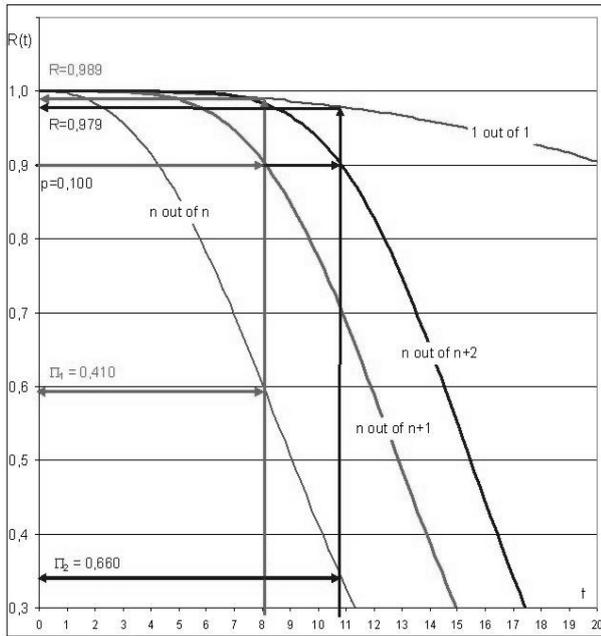


Fig. 4. Graphical interpretation of calculating new quantile orders at $t = 0$

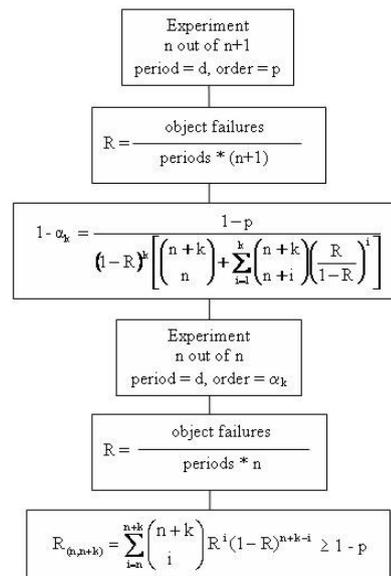


Fig.5. The procedure of applying new quantile order to the fleet of vehicles

Tab.2. Simulation experiments results (d = 3)

Number of:	Model			
	<i>n out of n+1</i>	<i>n out of n</i>	<i>n out of n+2</i>	<i>n out of n</i>
	$p=0.10$	$\alpha_2=0.40$	$p=0.10$	$\alpha_2=0.64$
- preventive replacements	3216	3170	1850	1814
- fleet unavailability	56	167	87	326
- objects failures	172	167	353	326
Empirical reliability of a vehicle	0.990	0.990	0.980	0.979
Empirical fleet unavailability	0.09	0.39	0.09	0.61

Simulation results in Tab. 2 show that the numbers of replaced elements in systems “*n out of n*” with $p = \alpha_1$ and “*n out of n+1*” with $p = 0.1$ are similar, as well as in systems “*n out of n*” with $p = \alpha_2$ and “*n out of n+2*” with $p = 0.1$. In both cases the fleet unavailability – calculated as $1 - R_{(n,n+k)}$ with use of formula (4) – is less than assumed p .

5. Conclusion

The application of the statistical control results in a considerable reduction in a number of incidental failures of vehicles, compared to a use without any prophylaxis. However, maintaining a high reliability of a fleet of vehicles is accompanied by a great amount of preventive replacements of vehicles. This means that there would be many more preventive replacements than random repairs of objects according to relatively low reliability of a single object.

Thus, it would be easier to achieve the required fleet availability by adding redundant vehicles which replace damaged one than to maintain a high reliability of the fleet of vehicles without redundancy. By adding a redundant object, more failures of vehicles can be accepted as well as a number of preventive replacements is reduced. Thus it would be useful to combine

redundancy and preventive replacement based on statistical diagnosing.

Required level of fleet reliability could be achieved by adding surplus vehicles and properly matching them with the quantile order applied to the main part of the fleet. By those two measures, random failures of the vehicles fleet are significantly reduced in number of replaced elements being much lower than those without redundancy.

The hereto presented method for setting a scope of preventive replacements, based on reliability properties of individual objects being used, allows for matching the parameters of replacements for applied reliability parameters of the objects.

Reliability analysis with respect to preventive replacements can be also performed with reference to objects’ elements being of critical importance for tasks that are executed. This analysis can be carried out for any set of compound objects that will jointly be used for execution of the tasks.

6. References

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