THEORETICAL ESTIMATION OF MAINTENANCE COSTS FOR PERIODICALLY CONTROLLED VEHICLES

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Abstract: *Periodic technical control is the monitoring of the vehicle's condition and the prognosis of its future status. Predictive maintenance decisions are also based on the results of the forecast. The paper proposes to perform a mathematical modeling of the predictive maintenance for the vehicles that are periodically controlled, respecting the procedure of a complete verification, using the specified equipment, metrologically calibrated. The efficiency of the periodic technical controls, in addition to the revisions recommended by the manufacturer, is evaluated by their costs based on their number. Mathematical models are proposed for calculating maintenance indicators for a Weibull distribution of time to failure. The aim is to reduce the costs related to them by maintaining the availability of vehicles in operation.*
Keywords: *predictive maintenance (PM); periodic technical control (PTC); maintenance cost.*

1. INTRODUCTION

The manufacturers of vehicles provide, in the user manual, time intervals or kilometers traveled for carrying out maintenance operations in order to ensure its availability in safe conditions for both occupants and other participants in traffic. The law provides for Periodic Technical Inspections for the same purpose. A maintenance strategy for vehicles is predictive maintenance (PM), which allows to recognize problems that may occur in the near future, predict wear and tear or accelerate aging and prevent damage or replacement of the affected component.

Ensuring the proper functioning of vehicles can be achieved by applying maintenance strategies and appropriate methods, based on regular monitoring of their operation. At the same time, periodic technical checks are recommended for early detection of premises of subsequent defect premises.

In this sense, an important role at the organizational level is the maintenance activity, as a support process that ensures the proper operation of the vehicles. As a result, the planning of maintenance activities must be carried out following the periodic monitoring and diagnosis of their operation by rationally applying, in relation to costs, the specific maintenance methods. The large number of publications related to various mathematical models and implementation techniques for different maintenance strategies denotes the major interest for the PM, both in order to maintain availability and to keep costs under control.

The paper [1] defines the concept of RCM - maintenance focused on reliability and the fundamental concepts of RCM. The process is used to determine the maintenance requirements of any physical asset in its operating context and discusses how the operation predicted by the user is ensured in the operating context of the user. Within the traditional maintenance management, the implementation and optimization of the specific maintenance policies and strategies are based mainly on cost and availability criteria [2]. The paper [3] aims to investigate the need for the use of inspection or monitoring devices to allow early detection of future defects to initiate PM. A systematic method is proposed to determine the optimal combination of inspection and verification methods to minimize the amount of control costs and system failure losses.

The proposed economic analysis methodology applies flexible decision procedures, depending on the conclusions expressed at the PTC - the periodic technical control for maintenance management. The models considered by the PM take into account the probabilities of the correct and incorrect decisions taken by the results of the periodic controls (PTC). The purpose of this paper is to develop a model for determining the cost of the PTC, correlated with the economic efficiency, under the conditions of the existence of a PM strategy. The decision rule is based on the evaluation of the maintenance costs, predictive and corrective, related to the costs generated by the non-operation of the vehicle. Based on the presented models it is possible to determine the optimal maintenance interval, taking into account an economic optimum. The developed model is then verified and validated by applying a case study, a car park of an organization, with its own maintenance service.

2. THE ECONOMIC PERSPECTIVE IN MAINTENANCE MANAGEMENT

Within the maintenance activities of the vehicles, the economic concept of cost, presents a great complexity, because it has a rich significance regarding the field, provenance, modality:

$$C_M = C_m + R_m \cdot \left(1 + \frac{r_s + r_i}{100}\right) + C_{ps} \quad (1)$$

where: C_M is the cost of maintenance, C_m is the cost of consumed materials, R_m is the remuneration of the directly productive personnel, r_s are the indirect expenses of the service workshop, r_i are the indirect costs of the organization, C_{ps} are the costs of the spare parts.

In the case of the technical revisions recommended by the manufacturer (RT2), these are interventions carried out in a systematic manner, respectively replacements of critical elements after a certain time interval (or kilometers). It follows that the optimal period of systematic intervention depends by the reliability function of the critical elements considered.

The reliability function can be defined by the following indicators:

- $\lambda (t)$ - failure rate;
- $R (t)$ - probability of survival (reliability);
- $F (t)$ - probability of failure (fall);
- $f (t)$ - probability density of defects.

In the case of intervention period t, within the systematic maintenance, RT2 in the case of the vehicle exposure, there is by definition a $F (t)$ probability of failure. Consequently, the total probable cost of maintenance and unavailability (Cts) will be given by the relation [6]:

$$Cts = Cd + Ci \cdot F(t) \quad (2)$$

where: Cd represents direct maintenance costs; Ci - indirect (additional) costs of unavailability in the event of a failure; F (t) - probability of failure.

In the case of the conditioned preventive maintenance, RT1 in the case of the exhibition of the vehicles, related to the evolution of a characteristic symptom, the average duration between two successive interventions, $M (t)$ is very close to the MTBF. It can be calculated by the relation:

$$M(t) = K \cdot MTBF \quad (3)$$

where: K is a coefficient of care taking into account the time required to reach the alarm threshold and the allowable threshold, in accordance with the preventive conditions of maintenance, can be very close to the number 1. Specify the preventive conditions of maintenance are a series cost of implementation a method of maintenance (for example, costs regarding the purchase of different devices for controlling and using a thing). These implementation costs are maintained under preventive conditions, between two successive interventions can be calculated according to the relationship:

$$Cc = \frac{A}{D} \cdot MTBF + Ca \quad (4)$$

where: Cc represents implementation costs of conditional preventive maintenance; A are the costs for purchasing the necessary measuring and control equipment; D is the likely life of these equipment; and Ca represents the costs of carrying out these controls and measurements for the critical systems considered, for a period of time equal to MTBF.

In the case of corrective maintenance, intervening after failure, the average cost per unit of time, ($\overline{C}tc$) will be:

$$\overline{C_{tc}} = \frac{Cd + Cc}{MTBF} \quad (5)$$

3. WORKING HYPOTHESES

The results of the periodic technical controls (RT1) are divided [7] into the following four categories:

- n_1 cases with symptoms of degradation or deterioration and they are detected, with probability p_1;
- n_2 cases when there are symptoms of degradation or deterioration, but they are not detected, thus, the failure occurs, with probability p_2;
- n_3 cases with vehicles in normal state, and RT1 indicates this result, with probability p_3;
- n_4 cases when vehicles are in a normal state, RT1 indicates deterioration or symptoms of failure (false alarm), with probability p_4.
- N the number of PTC till the moment τ.

$$n_1 + n_2 + n_3 + n_4 = N \quad (6)$$

$$p_1 + p_2 + p_3 + p_4 = 1 \quad (7)$$

If the vehicle failure occurs at time τ, $\tau \in [k\Delta t, (k+1)\Delta t]$, then p_1, according to the Weibull distribution function, for the introduction into maintenance, the probability p_1 becomes the failure rate (intensity), corrected with the probability p_{ptc} :

$$p_1 = Z(\tau) = \beta \cdot \lambda \cdot \tau^{\beta-1} \cdot p_{ptc} \quad (8)$$

where τ is a time parameter, β represents a shape parameter which by its values changes the allure of the variation curves of the reliability indicators, being able to model the behavior of the vehicles in different periods of the life of the devices (constant on intervals) and λ scale parameter which shows the extent of time distribution of the Weibull function (constant). The probability of the p_{ptc} is an average value that takes into account the facilities of the verification workshop and the competence of the personnel involved in this activity.

$$p_2 = \beta \cdot \lambda \cdot \tau^{\beta-1} \cdot (1 - p_{ptc}) \quad (9)$$

$$p_3 = (1 - \beta \cdot \lambda \cdot \tau^{\beta-1}) \cdot p_{ptc} \quad (10)$$

$$p_4 = (1 - \beta \cdot \lambda \cdot \tau^{\beta-1}) \cdot (1 - p_{ptc}) \quad (11)$$

4. ESTIMATE MAINTENANCE COSTS FOR PERIODIC PREDICTIVE CHECKS

To highlight the PTC, depending on cost of maintenance, the following will be considered:
- the time when the vehicle was immobilized as a defect, due to the lack of spare parts or the place at the control station, T_d
- the average time when the vehicle is repaired, t_{rc} , constant
- the time during the vehicle was checked periodically, t_{ptc} ,constant

The issue of determining the cost of a PTC depends on their number, noted with N.
The average maintenance cost becomes:

$$C_M = N \cdot \{ p_1 \cdot [t_{ptc} \cdot c_{ptc} + t_{rc} \cdot c_{rc} + (t_{ptc} + t_{rc}) \cdot c_{inl} + (t_{ptc} + t_{rc}) \cdot c_i + C_{ps}] + p_2 \cdot [t_{ptc} \cdot (c_{ptc} + c_{inl} + c_i) + t_{rc}(c_{rc} + c_{inl} + c_i) + C_{ps}] + p_3 \cdot t_{ptc} \cdot (c_{ptc} + c_{inl} + c_i) + p_4 \cdot [t_{ptc} \cdot c_{ptc} + t_{rc} \cdot c_{rc} + (t_{ptc} + t_{rc}) \cdot c_{inl} + (t_{ptc} + t_{rc}) \cdot c_i]\} + T_d \cdot c_{inl} \quad (12)$$

where: c_{ptc} is the cost of the labor per unit of time for the periodic verification; c_{rc} is the cost of the labor per unit of time for repair; c_{inl} is the cost per unit of time for car replacement; c_i is the cost per unit of time of the management of the organization and C_{ps} is the average cost of the spare parts per repair, values considered constant.
Substituting (1), (6), (7), (8), (9), (10) and (11) into (12) results:

$$\frac{C_M}{N} = \beta \cdot \lambda \cdot \tau^{\beta-1} \cdot (C_{ps} + p_{ptc} \cdot t_{rc} \cdot c_{rc} + p_{ptc} \cdot t_{rc} \cdot c_{inl} + t_{rc} \cdot c_i) + t_{ptc} \cdot (c_{ptc} + c_{inl} + c_i) + (1 - p_{ptc}) \cdot t_{rc} \cdot (c_{rc} + c_{inl} + c_i) + \frac{T_d \cdot c_{inl}}{N} \quad (13)$$

5. STATISTICAL APPROACH IN MODEL CALIBRATION

Statistical data were obtained on a group of 50 cars of the same manufacturer, the same models, with the years of manufactoring and commissioning 2005 (25 cars) and the rest in 2007. Of the cars manufactured in 2005, 3 were put out of circulation. after 13 years, 10 after 14 years and those manufactured in 2007 were withdrawn 2 after 12 years. The average lifespan is currently estimated at 13 years and an average turnover of 312000 km.
The statistical records took into account the life stages of the vehicles. The following data were obtained:
- periodicity RT1, considered Monthly Technical Control, with the acronym PTC, *monthly*
- the average time of RT1 is 2 hours, $t_{ptc} = 2$ *hours*
- the average time during vehicle was immobilized, without being in repair, $T_d = 3$ *days / year*
- the average time the vehicle repaired, $t_{rc} = 6$ *hours*.
- the cost of labor per unit (hour) of the periodic verification $c_{ptc} = 50$ *u.m.*;
- the cost of labor per unit of time of repair $c_{rc} = 50$ *u.m.*;
- the cost per unit of time of car replacement $c_{inl} = 12.5$ *u.m.*;
- the cost per unit of time of the organization management $c_i = 9$ *u.m.*;
- average cost of spare parts per repair $C_{ps} = 157$ *u.m.*.

where: *u.m.* represents monetary units (lei).
In stage of early failure, the following average values were recorded:
$N = 6; n_1 = 3; n_2 = 1; n_3 = 1; n_4 = 1$

During the following period, the one of operation:
$N = 114; n_1 = 28; n_2 = 61; n_3 = 19; n_4 = 14$
In the aging phase, the following average values were recorded:
$N = 36; n_1 = 25; n_2 = 8; n_3 = 2; n_4 = 1$
From above data, we obtain a weighted average of the probability of correct decision, $p_{ptc} = 0.69$ and values of β and λ:
$\lambda_1 = 1.02; \lambda_2 = 0.48; \lambda_3 = 0.03$
$\beta_1 = 0.75; \beta_2 = 0.98; \beta_3 = 1.94$
To be mentioned for $\beta < 1$, we are in rolling, for $\beta = 1$, we are in the life stage; and for $\beta > 1$, we are in the aging stage.

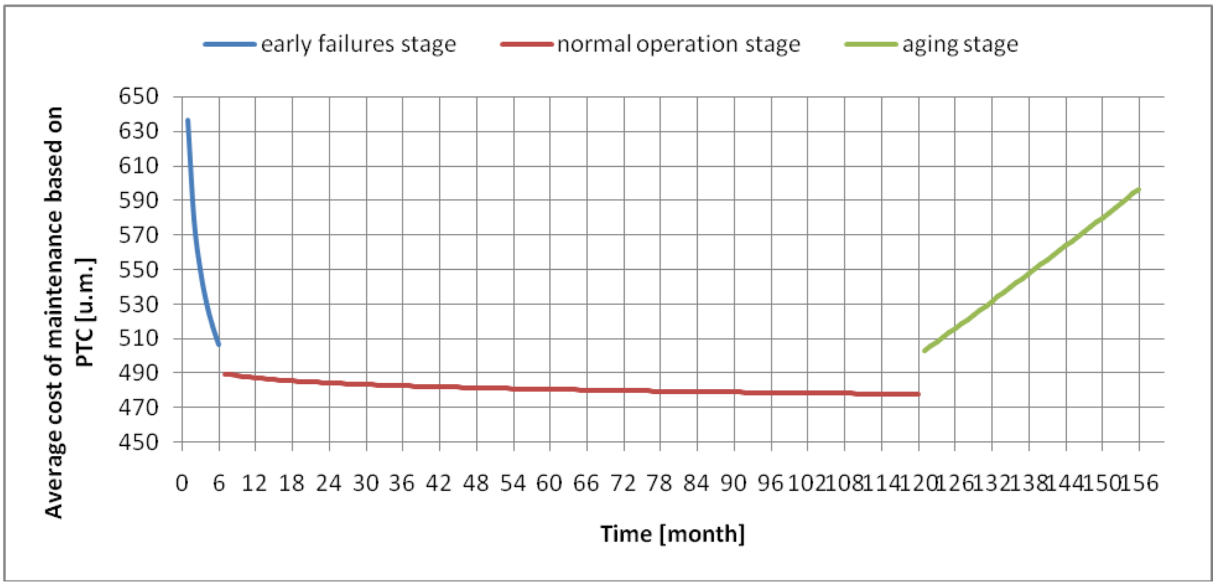

Figure 1: Estimated average cost of maintenance during periodic technical checks, RT1

The estimation of the average cost maintenance during the periodic technical controls, RT1, is illustrated in fig. 1. From the data collected and from the graph above, it can be observed that there can be no strict delimitation of the operating stages throughout the life cycle of the vehicle, there are jumps to applying the probability based on the failure rate given by the Weibull distribution. . The PTC reduces the total fixed assets of the vehicle and the cost of repair in case of defects in the course, but increases the cost of the predictive maintenance.

6. CONCLUSION

In this paper, we have proposed a new approach for the theoretical estimation of maintenance costs for periodically controlled vehicles. A credible average maintenance cost is obtained when each stage of the vehicle's operating life is analyzed separately. This will take into account the regime of urban, extra-urban or mixed exploitation. The novelty is the introduction of a probability of good diagnosis, related both to equipping the service with high performance equipment, as well as, especially, to the professionalism of the diagnostic and maintenance team.

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