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An evaluation method of preventive renewal strategies of railway vehicles selected parts

Indexed by:



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Highlights

- A method for evaluating the renewal strategies of wearing machine parts was developed.
- Calculations were made for a real case from railway operational practice.
- Obtained results indicate possibilities of improving the researched renewal strategy.
- The developed method is useful for services responsible for planning inspections.

Abstract

The aim of the work was to develop a method of verification of the preventive renewal strategies, which enables a simulation evaluation of the effects of the application of a specific schedule of inspections of parts that are important in the operation of complex renewable technical objects. Using it requires having an already established schedule of inspections, and the result of applying the method is determined by indicators that assess the usefulness of the strategy, even before implementation.

The developed computational tool was used to evaluate the renewal strategy of the current collector contact plates. Based on the real operational data, several renewal intervals were considered, determining the frequency of events involving the plate covering a specific mileage, from exceeding the wear control limit value to the next inspection (replacement). The proposed verification method is an important tool for testing and planning technical inspections for systems and elements with planned wear, and parts are periodically replaced.

Keywords

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preventive renewal, rail vehicles, renewal strategy, contact plates.

1. Introduction

The failures of technical objects that occur in the process of their use have various causes. In particular, failures caused by random factors and degradation processes of parts of machinery [8] (e.g. wear, fatigue, corrosion, erosion, ageing) can be distinguished, cf. [10, 11]. These processes start with the beginning of an object's use, and for a long time proceed with no significant impact on the object's proper operation (that is performing the required functions). The object, however, stops working properly when the impact of the degradation processes exceeds a certain threshold state (see [9]) resulting from structural conditions (excessive clearance between the interacting parts, inadequate cross-sectional area or a change of parts' geometric dimensions, excessive surface roughness of interacting parts, too large proportion of corroded surface in the overall surface, etc.). In such cases in order to enable further correct functioning of the object it becomes indispensable to regenerate or replace its failed parts [20].

In planning the process of an object's use and maintenance the important problem that should be analysed is (apart from the nature of the events leading to failure) the effects of failures. If the failure involves a threat or considerable losses (e.g. to human life and health, environ-

mental contamination, interruption in services provision, a secondary failure of other parts or subassemblies of a machine resulting from a primary failure of another part), the aim of developing an object's use and maintenance strategy is to prevent failures of this type [23].

The negative effects of failures resulting from the degradation processes of parts of technical objects can be restricted in several ways: continuous verifying of the object's technical state (monitoring and corrective maintenance actions if necessary) or preventive replacement of parts (when they are still in the availability state) [13, 18]. The determination of the optimum time of preventive replacement can be assisted by relevant preventive maintenance models in which reliability characteristics most frequently estimated on the basis of the data on objects' failures history are used. Such models include block replacement strategy, age replacement strategy, etc. [28]. When the information on the technical condition (the extent of elements' wear) can be obtained while the object is working a condition-based maintenance strategy can be employed, which is sometimes more effective [17, 27].

Technical means subject to intensive wear during their use [2, 3], whose replacement is most frequently caused by their reaching a cer-

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tain limit value of a given dimension (which is detected in a scheduled inspection) include current collector contact plates used in rail vehicles. Their correct operation determines the proper interaction of the vehicle with the transport infrastructure and proper electric power supply of the vehicle itself, cf. [15]. This translates into operational safety and continuity of the provision of transport services, which determines the economic results of carriers [25]. Problems of this kind are discussed in many studies [13].

In the present paper an original maintenance strategy verification method is proposed. It enables the simulation-based estimation of the effect of the adopted inspection strategy of parts most significant in the rail vehicle use (cf. [19]). It was assumed that in the framework of inspection procedures the current technical condition of tested current collector contact plates is estimated and (each time) the decision is taken as to their replacement or further operation (until the next scheduled inspection). It was also assumed that the given contact plate, degrading during operation, should be replaced on exceeding a limit control value of its wear (cf. [4]). This value is selected with a certain allowance so that the contact plate that has exceeded it owing to wear continues to operate correctly (for some time). Consequently, the assumed wear control limit value is not identical with the wear extent at which the contact plate can no longer perform its function (fails).

The proposed method is a tool assisting the technical services who schedule the inspection periods, helping them select preventive maintenance strategies that should deliver better results of the actual use of objects. This method is, then, not a typical maintenance scheduling model – understood as a mathematical model serving merely to determine the optimal periods of preventive replacement of objects. Its application requires a certain predefined inspection schedule, and its result is expressed with numerical indicators that provide an evaluation of the usability of the proposed strategy before it is implemented. These results can be referred to the evaluation of other (modified) strategies in order to select one that yields the most favourable effects or better fits in with maintenance project of the given object.

In practice also other strategies of current collectors use, facilitating their maintenance, but requiring the contact plates and current collectors of a certain design are employed. In one of these state-of-the-art technical solutions are applied which enable automatic taking the current collector out of operation on its exceeding the wear control limit specified in the design. In such emergency situation the safe solution is to drop the current collector to avoid its contact with the overhead line, which prevents damage to the interacting elements. This is done by a group of solutions called ADD (Automatic Drop Devices) by one of the leading manufacturers of current collectors – STEMMANN-TECHNIK [30]. The most popular ones are based on two technologies, mechanical and pneumatic. In the former one, when the current collector shoe rotation exceeds the allowable values (e.g. due to a collision with a broken element of the contact wire) the mechanism loosening the tension spring that holds the current collector in the top position is activated – the collector is dropped automatically [31]. The other solution is based on the pneumatic system in which the pressure that allows the current collector to be raised to the top position is maintained. When the pressure is inadequate, the current collector cannot be raised. A breach in the pneumatic circuit means pressure drop – in the matter of seconds the collector returns to the lower position. This can happen in the case of allowable limit wear of the graphite contact plate being reached – when the relevant friction device is damaged, the contact wire gets into contact with the compressed-air conduit in the current collector shoe, which becomes worn. When the pneumatic system is breached, the pressure is reduced and the current collector is dropped even before damage.

Owing to the application of the solutions described above the contact plate can be in operation to the value of the wear allowable limit, due to which it can be fully used over the entire durability and the moment of its failure is recorded accurately. The employment of this fact for inspections intervals optimisation will help make the maintenance

processes management more effective, which will result in both the financial result and the reduction of the number of failures as well as cases of using current collectors whose contact plates exceed the wear control limit values.

Although there are technical solutions that enable frequent, automated evaluation of the technical state of current collector contact plates [13] or taking out of operation the current collectors whose contact plates have been worn completely with no secondary, costly damage, it is still useful to predict and estimate the vehicle mileage to the moment of the collector contact plate reaching the limit value of wear, cf. [6]. Firstly, it enables planning in advance maintenance procedures connected with contact plates replacement, following which requires the provision of an adequate number of staff, service stands, tools and spare parts (new contact plates), cf. [14, 16]. Maintenance works planning, in turn, provides a basis of estimating the operating costs [1]. Secondly, when the presented design solutions of current collectors are not used in vehicles, it is indispensable to schedule their inspections adequately to the needs resulting from the durability of their parts so as to prevent their reaching the wear control limit while the vehicle is being used. Thirdly, if the solutions based on taking out of operation the current collectors at the moment their contact plates have been worn completely were employed and if the only maintenance strategy was their post-failure replacement, the reliability of vehicles would be affected negatively as they would be used regularly with a (at least one) unavailable current collector.

In view thereof, the design solutions based on degraded current collectors being automatically taken out of operation seem a valuable protection against serious consequences of uncontrolled wear limit being reached by a contact plate. The technical solutions of automated measurements of contact plates may definitely facilitate the scheduling of parts replacement over a short time horizon. However, the operation process course and costs planning over a longer time horizon requires the application of the tools of the theory of reliability and the renewal theory [24, 26].

2. Characteristics of the proposed calculation model

To enable the evaluation of the expected results of the application of the inspections schedule and renewal strategy a simulation calculation model has been developed.

Figure 1 presents a division of object's operation time horizon (T_H) into intervals. It is based on periodical inspections performed to detect whether the wear control limit has been exceeded, according to a defined schedule.

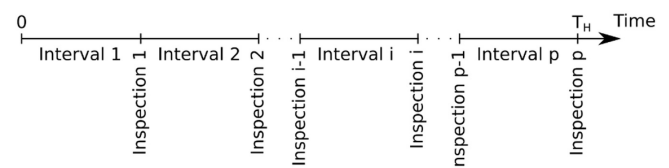


Fig. 1. Object's operation time horizon division into periodical inspections-based intervals

After exceeding the wear control limit the object continues to operate until the next periodical inspection during which it is detected. The time to inspection, shown in Figure 2, between exceeding the wear control limit and the next inspection, is particularly important because of inspection scheduling and determination of the wear control limit.

To estimate the time to inspection the simulation method, whose general description can be found in [21], was used. The graph of transitions for an object's reliability-operation states is shown in Figure 3, where the absorption state denotes the object's unavailability state.

An algorithm of a single iteration is shown in Figure 4, where object's operation time horizon in simulation was marked as T_H .

The proposed algorithm for obtaining simulation data has been employed for the evaluation of several renewal strategies of a selected technical object.

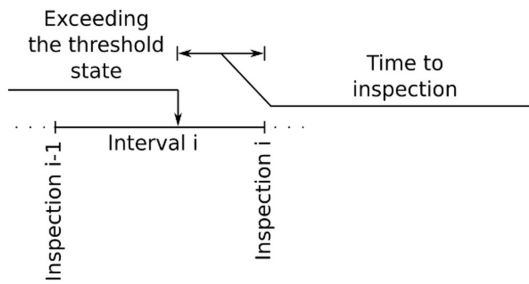


Fig. 2. Time to next inspection in the interval in which wear control limit has been exceeded

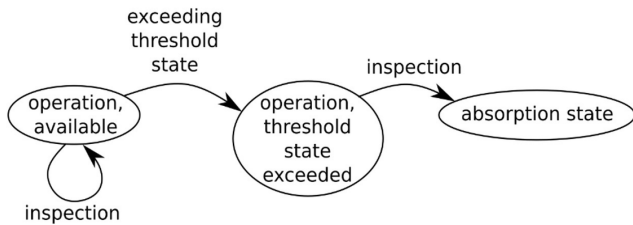


Fig. 3. Transitions of an object's states

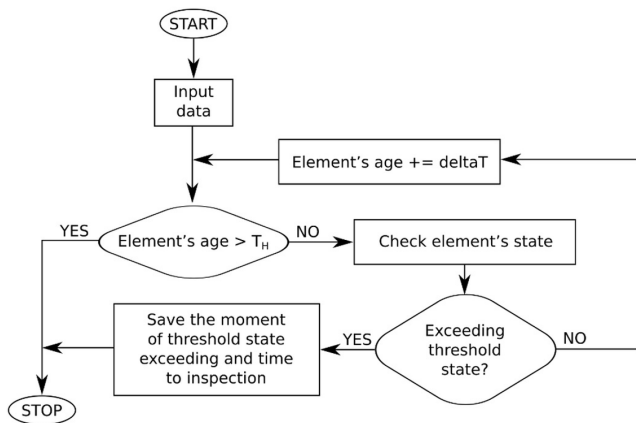


Fig. 4. Algorithm of simulation single iteration

3. Characteristics of the tested object and data on its failures

The study was performed for rail vehicle current collector contact plates, in which case the technical condition inspections are a basis for the decision of the object's replacement or continuation in the operation state until the next scheduled inspection. Contact plates belong to very important elements that guarantee the continuity of current flow between the overhead contact line and the vehicle [5, 6]. These elements, small in dimension, must meet the requirement of good electrical conductivity in a variety of atmospheric conditions while preserving low friction coefficient as the current is drawn with a vehicle in both standstill and in motion, not infrequently at a very high speeds [3, 12, 22].

Overhead contact lines are made of copper which has very good electrical properties and adequate resistance to both mechanical and climate induced failures. When contact plates are also made of copper high strength current can be drawn (over 1200 [A]), which is needed for the start-up of heavy trains. The possibility of high currents transfer is counterbalanced by the unfavourable properties of the contact joint of two elements made of the same materials – the static friction coefficient of such a joint is 1,5. It is reduced by the contamination of surfaces with oxides, but this phenomenon improves resistance. Owing to the above, the contact plates made of copper are subject to relatively high abrasive wear despite the fact that their design envis-

ages the application of lubricants between the contact plates mounted on the shoe [32].

In Poland contact plates made of graphite are much more commonly used. The material contains 85% carbon and the other components are copper and other additives. Carbon plates have very good friction coefficient which does not exceed 0,15 for the connection with the copper wire of the overhead contact line. The chemical composition of a given contact plate is modified according to its application – conduction of very high currents [2]. Moreover, carbon plates are a cheaper solution (mainly due to the limited percentage of expensive copper) [32].

In 2011 the Polish Railways (PKP Polskie Linie Kolejowe S.A.) introduced obligatory use of graphite contact plates on the lines under their control [25].

Regardless of the contact plate used, the nature of the current collector's operation inherently involves abrasive wear of the contact elements [7, 12, 29]. Exceeding the wear control limit of the contact plate may result in serious consequences – from degraded quality of current conduction, failure of the whole current collector, to breaking the overhead contact line. Therefore, very strict monitoring of this element is extremely important, because its timely replacement guarantees trouble-free operation and no need for costly and long-lasting failure.

The current collector can be monitored visually at any time. Then, any point damage that may lead to contact plate failure can be easily detected. The method of current collector's failures evaluation in the scope of employed devices and inspection intervals depends on the individual practice of the operator. It takes place regularly (e.g. every 3 000 [km]) and on its basis decision is taken as to the contact plate's replacement or its continued operation until the next inspection.

To estimate the probability distribution of the operation time-to-replacement of all of the selected current collector contact plates the data gathered in the operation and maintenance of several dozen electric locomotives series EU07, in which AKP 4E type current collectors are employed – shown in Figure 5, were used.

On the basis of these data tests of the goodness of fit of the operation time to wear-induced replacement (expressed in the mileage in kilometers) with theoretical probability distributions (Weibull, normal, exponential, gamma) were performed. For this purpose Statistica 13.1 software was used. After Kolmogorov-Smirnov test and χ^2 test, the best fit was obtained for three-parameter Weibull distribution. The tests were performed at the significance level of $\alpha = 0,05$. The results are given in Table 1 and Figure 6.

The probability density function and values of the estimated parameters of three-parameter Weibull distribution were adopted as formula (1):

$$f(t) = \alpha \left(\frac{1}{\beta}\right)^\alpha \cdot (t - \theta)^{\alpha-1} \cdot \exp\left(-\left(\frac{t - \theta}{\beta}\right)^\alpha\right); t > \theta \quad (1)$$

where:

- $\beta = 17,007 \cdot 10^3$ [km] – parameter of scale,
- $\alpha = 1,361$ – parameter of shape,
- $\theta = 10 \cdot 10^3$ [km] – parameter of shift.

In the data set under consideration, no object was replaced because of the dominant forms of wear of the contact plates, which resulted in their thickness decreasing before reaching the mileage of 10000 [km].

The inspections schedule and replacements strategy which in their basic version (applied for the sets of contact plates analysed in the presented study) lies in a periodic inspection of plates' technical condition and the decision taken on this basis as to their replacement, together with the adopted probability distribution of plates' time-to-replacement were used for the presentation of the calculation model proposed in the paper.

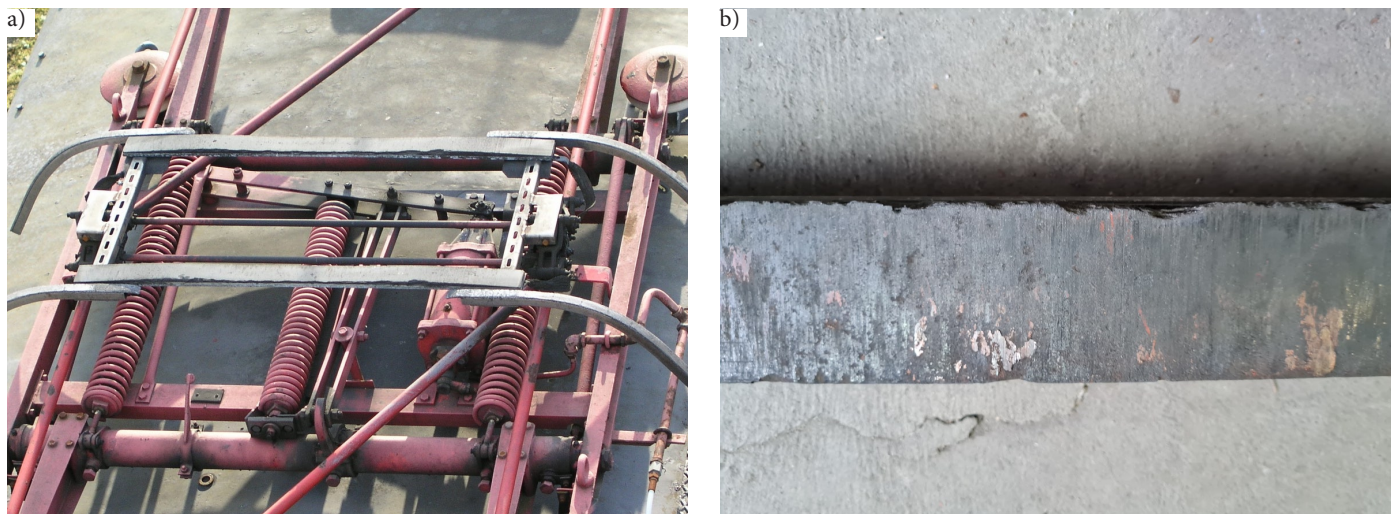


Fig. 5. AKP 4E: a) current collector; b) an example of a contact plate

Table 1. Results of test on data goodness of fit with Weibull shifted distribution

Distribution	Characteristic value in test K-S	Test K-S p-value	Characteristic value in test χ^2	Test χ^2 p-value
three-parameter Weibull	0,0825	0,980	0,483	0,785

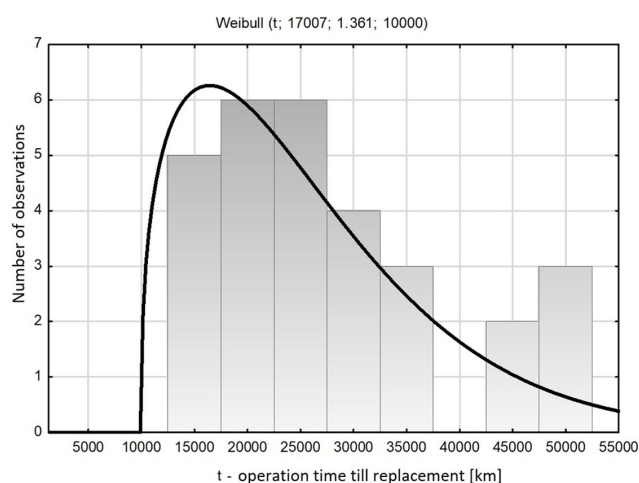


Fig. 6. Histogram of data and density function of three-parameter Weibull distribution

4. An example of an analysis of preventive renewal strategy

In the framework of verification of the developed calculation model simulation experiments were performed for the statistically determined probability distribution. This distribution reflects the operation-to-replacement mileage of a contact plate, which replacement was done based on the plate attaining or exceeding the adopted contact plate wear control limit. This means that this distribution was obtained only on the basis of the values of mileage which are a multiple of inspections interval. In the presented analysis, however, it is used as a model on the basis of which the potential moments of exceeding the wear control limit are identified by means of simulation. In the simulation experiment, as in real-life practice, the maintenance (replacement) as a response to this fact, can be undertaken only during the inspection, that is at one of the moments established in advance resulting from the inspection scheduling. However, in the experiment the potential mileage during which the wear control limit has been

exceeded is simulated accurately, which allows checking the delay-time between contact plate wear control limit being exceeded and the plate replacement. It is additionally assumed that in simulation the replacement of the contact plate whose thickness is close to the wear control limit, which sometimes occurs in the real operation, is never performed. It should be emphasized that in the simulation experiment the replacement can take place only after this value has been exceeded, in the forthcoming inspection. For this reason, all the contact plates used in simulation work longer (if only for a short while) than until the wear control limit is exceeded.

The calculations were performed for five different (3, 6, 12, 18 and 36 [thousand km]) fixed values of mileage after which the current collector scheduled inspection is done. In each experiment the moment of attaining the contact plate wear control limit defined with an accuracy of 100 [km], the simulation time horizon is 72 [thousand km], and the number of iterations 10 thousand. As assumed before, the contact plate is replaced only after its wear control limit has been exceeded, during the nearest inspection (so there are no typical preventive replacements). Another assumption was that this limit had been selected with a certain allowance so that its being exceeded does not involve any immediate interference in the object's proper functioning. The result of each iteration is the mileage that the given contact plate covers from the moment of attaining the limit wear to the nearest scheduled inspection (which equals its replacement).

Figures 7 – 11 illustrate the frequency of events of a contact plate covering a certain mileage, from exceeding the wear control limit until the forthcoming inspection (replacement). In each case these events are analyzed for subsequent mileage ranges of 1 [thousand km] preceding the inspection.

The obtained bar charts illustrate the dependence of the expected distribution of mileage (the usage time) after exceeding the wear control limit on the fixed inspections (interval) schedule. It is far from obvious when only the initial probability distribution is analysed. As can be seen, subsequent cases of exceeding the wear control limit add up to others within individual intervals preceding inspection.

The analysis indicates how long the given part of objects continues to be used after the wear control limit has been exceeded. It is useful in the evaluation of the analysed inspection schedule and renewal strategies because the proportion of objects that will be used over an excessive period of time can be identified. And it should be remembered that the wear control limit considered in this study is nominal in nature and is not equivalent to the wear extent which prevents proper functioning of an object. A settled wear control limit is therefore merely a supporting value, indispensable in taking the decision of an object's replacement. Since the level at which an object no longer op-

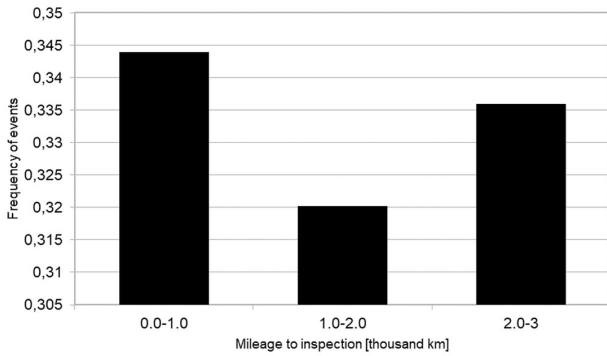


Fig. 7. Histogram of mileage from exceeding wear control limit to forthcoming inspection (replacement) for inspection intervals of 3 [thousand km]

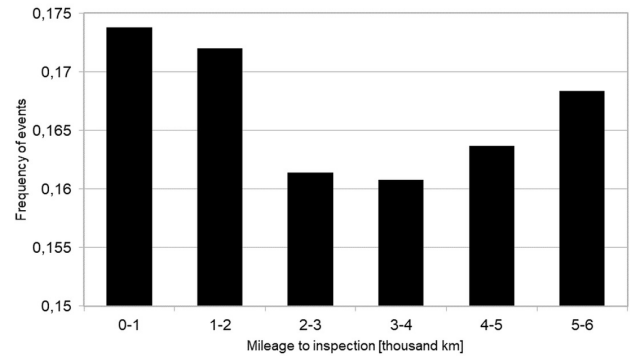


Fig. 8. Histogram of mileage from exceeding wear control limit to forthcoming inspection (replacement) for inspection intervals of 6 [thousand km]

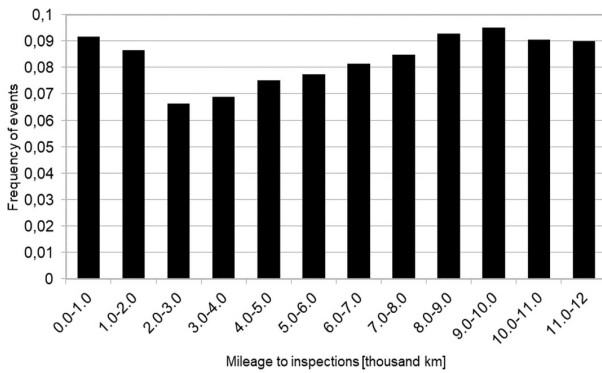


Fig. 9. Histogram of mileage from exceeding wear control limit to forthcoming inspection (replacement) for inspection intervals of 12 [thousand km]

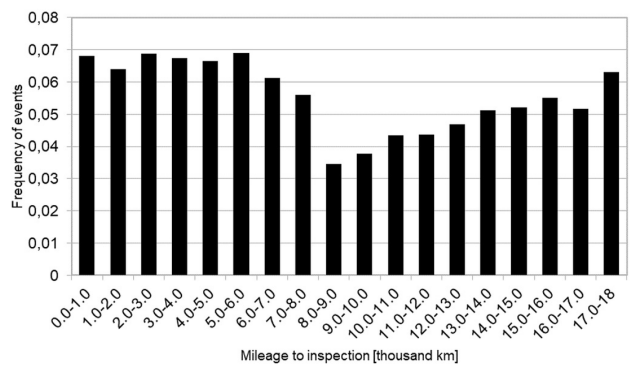


Fig. 10. Histogram of mileage from exceeding wear control limit to forthcoming inspection (replacement) for inspection intervals of 18 [thousand km]

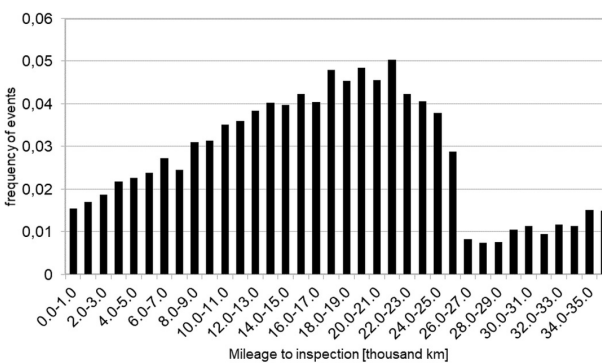


Fig. 11. Histogram of mileage from exceeding wear control limit to forthcoming inspection (replacement) for inspection intervals of 36 [thousand km]

erates correctly must be prevented, it should be replaced beforehand. The replacement should be performed at the mentioned settled wear control limit. A natural consequence of such an approach is that the selected wear control limit should guarantee the safe use of the object until the next inspection during which this value being exceeded will be identified. On the basis of the analysis of the presented results it can be stated what proportion of objects is used for a period longer than allowed by the selected allowance resulting from the adopted nominal allowable wear threshold, which is an estimate of a risk of the occurrence of a serious failure. An analysis of the presented results therefore indicates for how long (over what mileage) what number of contact plates is used after the adopted wear control limit has been exceeded, which constitutes an evaluation of the threat of the occurrence of a severe failure.

In the case of the use of the contact plates of AKP 4E current collectors in EU07 electrical locomotives, discussed in the present study, the probability of attaining the contact plate wear allowable limit can be established for each of the proposed inspection schedules.

According to the operational specifications, contact plate worn thickness g – from the nominal value to the wear control limit after which it is replaced as scheduled – is 12 [mm]. Between the wear control limit value and the wear allowable limit a thickness margin g_z of 5 [mm] is adopted. In accordance with the adopted probability distribution of contact plate wear, for the operational data specifying the contact plate wear control limit, the wear by the value of g occurs after the mileage of at least 10000 [km]. On this basis the contact plate maximum wear z_{max} per a mileage kilometer can be estimated:

$$z_{max} = \frac{g}{\theta} = \frac{12}{10000} = 1.2 \cdot 10^{-3} \left[\frac{\text{mm}}{\text{km}} \right] \quad (2)$$

On this basis an approximate estimation can be made (assuming the same wear mean rate) of the shortest mileage x_{min} after which the thickness margin g_z is used up if the wear control limit is attained between inspections:

$$x_{min} = \frac{g_z}{z_{max}} = \frac{5}{1.2 \cdot 10^{-3}} = 4167 [\text{km}] \quad (3)$$

This value enables the identification of the potential numerical proportion of working contact plates after reaching the wear allowable limit, that is, after the margin g_z is completely used up before the next inspection. This value can be specified for each inspection schedule analyzed in the presented simulations. The contact plates estimate numerical proportion indicates the probability that the contact plate will reach the wear allowable limit before the next inspection, which means that the current collector's proper operation will be disturbed. The probabilities in the proposed strategies are given in Table 2.

As can be noticed, the schedule with inspections every 3000 [km] mileage nearly ensures that the contact plate will not reach the wear

Table 2. Probability of contact plate reaching wear allowable limit in various inspection schedules determined with the use of the lowest mileage value till the margin g_z is completely used up

Mileage between inspections in schedule [km]	3000	6000	12000	18000	36000
Probability of contact plate reaching wear allowable limit	0	0,305	0,674	0,721	0,923

Table 3. Probability of contact plate reaching wear allowable limit in various inspection schedules determined with the use of the expected value of the mileage till the margin g_z is completely used up

Mileage between inspections in schedule [km]	3000	6000	12000	18000	36000
Probability of contact plate reaching wear allowable limit	0	0	0,120	0,378	0,743

allowable limit between inspections, even in this pessimistic version which allows the fastest possible consumption of the g_z . This inspection schedule is employed by the operator of the contact plates analyzed in the study. In the other schedules the probability of contact plate reaching wear allowable limit is greater. Based on the results obtained, however, it can be stated that the zero probability of contact plate reaching wear allowable limit between inspections could also be attained by lengthening the period between inspections up to 4000 [km], that is, by about 30% compared with the schedule employed at present.

If, however, the expected value $E(T)$ of contact plate were after an adopted distribution was used as a basis, the analysis would be:

$$E(T) = \Gamma\left(1 + \frac{1}{\alpha}\right) \cdot \beta + \theta = 25573 \text{ [km]} \quad (4)$$

$$z_{sr} = \frac{g}{E(T)} = \frac{12}{25573} = 0.47 \cdot 10^{-3} \left[\frac{\text{mm}}{\text{km}} \right] \quad (5)$$

$$x_{sr} = \frac{g_z}{z_{sr}} = \frac{5}{0.47 \cdot 10^{-3}} = 10638 \text{ [km]} \quad (6)$$

For such a case, the probabilities of contact plate reaching wear allowable limit before the next inspection in the discussed strategies are shown in Table 3.

On the basis of the expected value of mileage x_{sr} after which the contact plate thickness margin g_z is used up, the schedule with inspections every 6000 [km], as the schedule with inspections every 3000 [km], gives a zero value of probability of contact plate reaching wear allowable limit between inspections. The results, however, should be interpreted remembering the fact that the margin g_z may be used up at a mileage smaller than would result from the expected value. Such an approach introduces a broader range of uncertainty in decision taking and increases the risk that might not be acceptable to the operator.

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5. Conclusions

The proposed algorithm enables an evaluation of the expected effects of inspections schedule and renewal strategy of given objects, and the analytic method defines a procedure applicable for the comparison of the effects of various strategies in order to select the most favourable one to apply in practice (without direct consideration of the cost of inspections and the

effects of failures).

In the studied case, the analysis of the results leads to a conclusion that lengthening the intervals between inspections by 1000 [km] (inspection every 4000 [km]) is safe. Such lengthening the intervals between inspections is justified economically and, moreover, offers the probability of contact plate reaching wear allowable limit acceptable to the operator. It should, however, be remembered that the intensity of contact plates' wear differs with the seasons of the year, which may be the subject of further, more detailed analyzes. The proposed method makes it possible to change the model used and conduct analyzes for various conditions and wear processes.

The potential of the proposed model can be further developed to include a differentiation of object's age-based inspection intervals, depending on the contact plate's mileage. Higher inspection rate prior to the expected wear control limit being reached enables restricting the working time after this value has been exceeded thus providing a basis for the reduction of the reserve (surplus) of the material of the degraded parts. It is conducive to more effective use of contact plates in the aspect of their actual operational durability.

To ensure the operational safety of the discussed types of current collectors, the solution proposed in the present study can be used successfully. And when the design allows, automation-based modern solutions of taking out of operation the collector with worn contact plate can be introduced additionally. The statistics-based forecasting models facilitate inspections scheduling and spare parts management, and the state-of-the-art diagnostic and design solutions help better use degrading parts thus protecting against failures resulting from, *inter alia*, the imperfections of forecasts.

The proposed method is an important tool for testing and planning of inspection schedules for systems and elements which are subjected to expected operational wear, and parts are replaced in a cyclic formula.

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