Pantograph Strips Failure Analysis and Artificial Intelligence Prevention Methods

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Reliability and operational safety of the railway transport in large part depends on the correct reception of power from the catenary by a traction vehicle. In this paper, a special attention was paid to consumption of sliding strips of a current collector (AKP-4E and 5ZL type), measured during periodic reviews of locomotives EU07 and EU09. Pantograph data, collected during periodic technical reviews, was provided by one of the biggest railway carrier in Poland.
To investigate the reliability assessment of the selected pantograph strips a non-destructive degradation analysis was carried out. On the basis of the wear measurements of the strips and the critical value of wear, the failure distribution model was developed. It was used to obtain the selected reliability characteristics and to predict the lifetime of the strips.
In next step, failure analysis was conducted. Such analysis was carried out for two variants to compare the effectiveness of Artificial Intelligence Prevention method. In the first variant, analysis was based on data selected during standard technical review of a pantograph. Second variant considered Artificial Intelligence method to predict and prevent cases of pantograph strip damage. Applied and tested methods of artificial intelligence were mainly related to classification algorithms. For this purpose was used techniques such as: decision trees (Complex Tree Medium Tree, Simple Tree), supporting vector machines (Linear SVM, Quadratic SVM, Cubic SVM, Fine Gaussian SVM, Medium Gaussian SVM, Coarse Gaussian SVM), methodic of nearest neighbors (Fine KNN, Medium KNN, Coarse KNN, Cosine KNN, Cubic KNN, Weighted KNN) or classifiers (Boosted Trees, Bagged Trees, Subspace Discriminant, Subspace KNN RUS Boosted Trees).
The results of conducted analyzes may be used to build a preventive maintenance strategy of the pantographs. The applied reliability models of wear propagation can be extended by the parameters of the cost and repair time becoming the basis for estimating the costs of operation and maintenance.

Keywords: *Reliability Assessment, Failure Distribution Model, Pantograph Strip, AI Methods, Machine Learning, Artifitial Neural Network, Damage Prevention*

1. INTRODUCTION

Reliability and safety during technical operation of the railway vehicels depend largely on the correct power reception from the catenary system by a traction vehicle. Currently, there are many scientific papers regarding the pantograph–overhead catenary system. These works concern mainly numerical methods of simulation of dynamic phenomena [1–7], analysis of contact force [8–15], as well as wear of sliding strip material [16–24]. The papers focus particularly on material properties depending on the composition of the strip. A wide interest in the problems of the pantograph–overhead catenary system results from the desire to ensure the best cooperation and reduce the operating costs.

Technical condition of pantograph is checked on every technical review. According to the preventive maintenance strategy related to the pantograph, we distinguish the following activities:

- control reviews (every 2 - 4 days),
- periodic reviews (once a month),
- large reviews (every 250 thous. km ± 10%),
- smaller repair (every 500 thous. km),
- bigger repair (every 1000 thous. km),
- major repair (after the course of 4000 thous. km).

During each review, among other things, a visual inspection of a current collector is made which takes into account checking the current collector components without disassembly.

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A component which is in direct contact with contact wire of overhead catenary line is a carbon sliding strip. Because of that, when strip is damaged, it can cause danger and expensive damages to catenary line. The problem associated with the correct determination of the technical condition is therefore very important. In this paper, a special attention was paid to consumption of sliding strips of a current collector (AKP-4E and 5ZL type), measured during periodic reviews of locomotives EU07 and EU09.

2. PANTOGRAPH SLIDING STRIPS

A verification of slides state is performed on every technical review. At the time of examination it should be remembered that sliding strip exchange can be caused by three types of destructive processes – wear and small failures caused by wear; failures of a sliding strip; and changes in pantographs' regulations.

a) b)

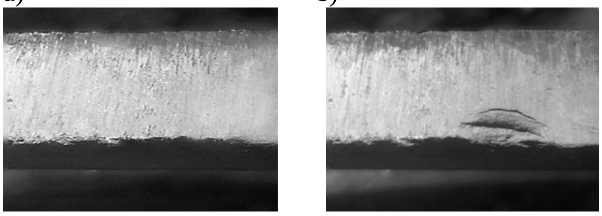

Figure 1. Damages of the edge of carbon sliding strip: a) minor surface damages; b) major surface damages

In case of wear a reduction in the thickness of strip may be noticed, as a result of the abrasion processes and electro-eroding phenomena. The wear process has approximately monotonous change in the thickness of the sliding strip.The reason for replacing the sliding strip in this case is exceeding the recommended strip thickness. If some small defects will occur during which do not cause loss of the strip ability of current collection – e.g. wear of the edge of the strip – there is no need to replace the strip (Fig 1a).

a) b) c) d)

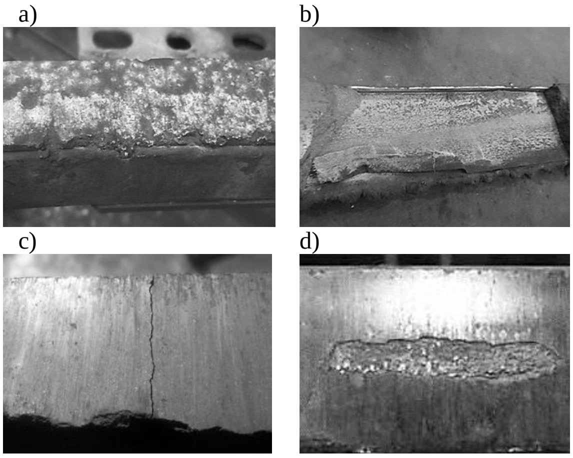

Figure 2. Wear of sliding a) material melting as a result of arcing; b) detachment of piece of carbon strip; c)crack of a strip; d) peeling off the top layer of a strip [25]

Such failures are caused by impact on the hard points of catenary and it is often assumed that minor surface damage may not exceed 30% of the surface of the carbon strip. However, if there is one major damage (Fig 1b), the strip should be replaced, because it may damage the overhead line.

In case of replacement caused by damage, there are undertaken steps aimed at evaluating criteria such as:

• material melting as a result of arcing and damages caused by arcing (Fig. 2a),
• detachment of a piece of carbon strip (Fig. 2b),
• cracks of a sliding strip (Fig. 2c),
• peeling off the top layer of a carbon strip Fig. 2d).

During maintenance there are also some changes in pantograph regulations, which can caused uneven wear of sliding strips. In such case, if the difference in strip thickness is big, the strips should be replaced. If the thickness is different in a strip but acceptable, then then the slide should be turned 180 degrees.

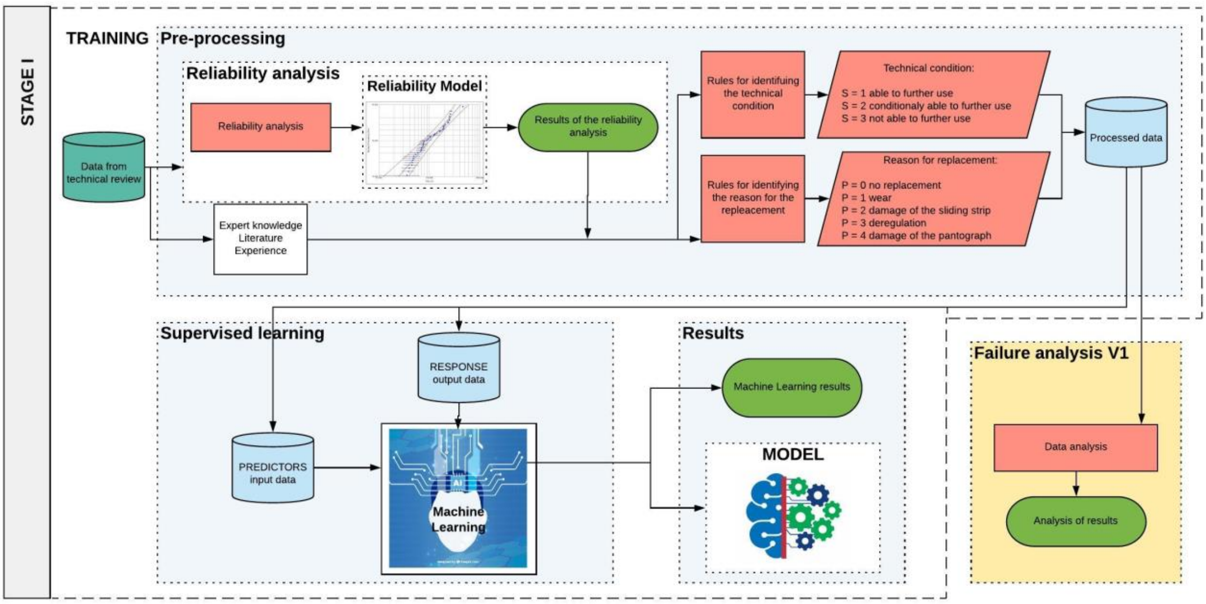

Figure 3. Metodology first step – Machine Learning and failure analysis for variant I

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3. METODOLOGY

In order to reduce the number of damage to the strips, a model based on the Machine Learning was applied. In order to develop such a model, it was necessary to process the archival data by the supervised learning method, and then to select and to make an implemention of the best predictive model for simulation.

This method is presented in detail in Figure 3 and Figure 4. Figure 3 shows the first stap of anaylsis in which, apart from training, damage analysis was made according to archival data (Variant I). The second step, presented in Figure 4, contains the prediction of ~~the~~ technical condition of the current collector and the damage analysis for the data modified in accordance with the prediction results (Variant II). Step I includes also the reliability assesment for the further processing of the output data.

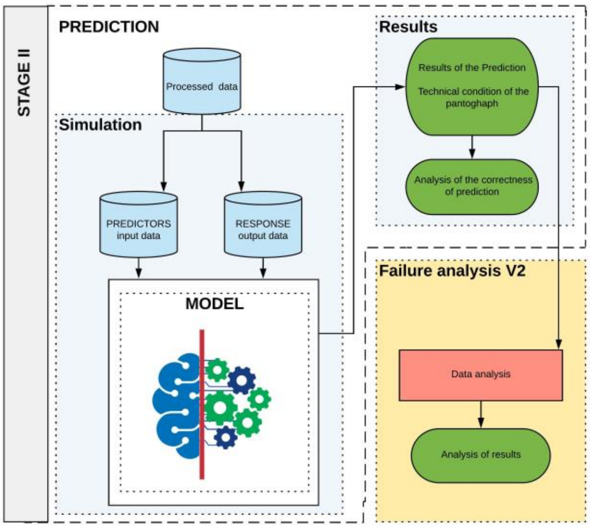

Figure 4. Metodology second step – Prediction and failure analysis for variant II

3.1 Reliability Assesment

Based on the technical reviews of the locomotives types EU07 and EU09, the empirical data were collected which correspond to the failures of the selected pantograph types. The data were analysed according to the Weibull analysis [IEC 61649:2008 Weibull analysis] and the parameters of 2-p Weibull distribution were obtained, as shown in the Table 1. The Weibull parameters were calculated using the Maximum Likelihood Estimation method included in Reliasfoft Weibull++ software, which allows to take into account the confidence bounds.

Tabel 1. Parameters of Weibull distribution for the analysed types of pantograph

Parameters of Weibull distribution	DSA-150	AKP-4E	5-ZL
β	1.470337	1.153632	1.329664
η (days)	74.619087	119.655763	134.032580

Goddness of fit for the considered Weibull distribution with two sided confidence bounds on reliability with significance level of 0.05 for the selected pantograph types are shown in the Figures 6a-c.

Probability density function for the Weibull distribution is given as follows [1]:

$$f(t) = \frac{\beta}{\eta^{\beta}} t^{\beta-1} exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \qquad (1)$$

Based on the calculated parameters of a Weibull distribution, a probability density function may be plotted in order to compare the values of time at which the probability of occurrence of failure reaches the maximum, $t_{f=max}$ (Figure 5). This will be the basis for the further failure analysis and supervised machine learning.

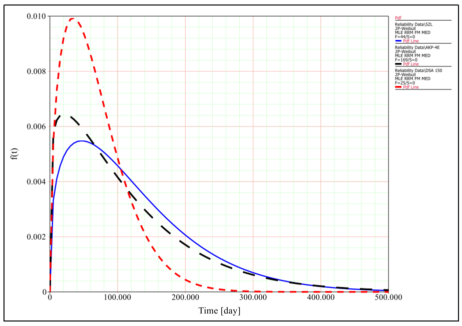

Figure 6. Probability density function for th selected types of pantograph: a) DSA-150, b) AKP-4E, c) 5-ZL

where:

$\beta - shape\ parameter$

$\eta - scale\ parameter$

a) b) c)

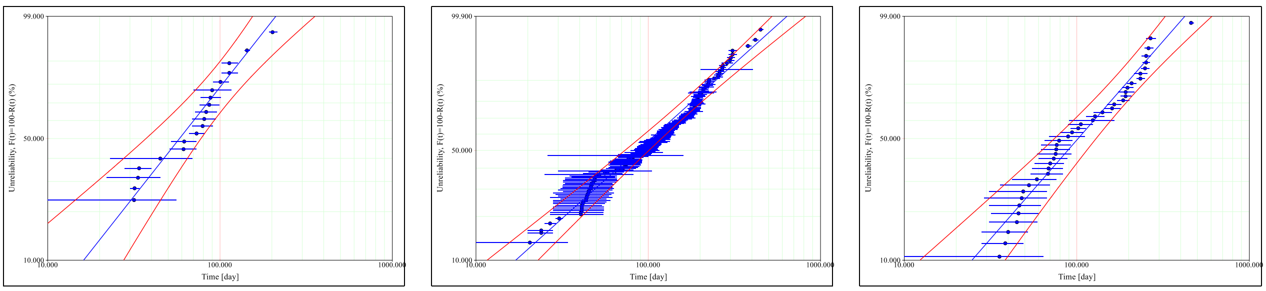

Figure 5. Weibull Probability plot for th selected types of pantograph: a) DSA-150, b) AKP-4E, c) 5-ZL

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Based on the probability density function, a mean time to failure may be calculated as:

$$MTTF = \int_0^{\infty} t \cdot f(t)dt \qquad (2)$$

The vaules of MTTF and $t_{f=max}$ are presented in the Table 2.

Table 2. Calculated MTTF and $t_{f=max}$ parameters for the selected types of pantographs

Type of pantograph	MTTF (day)	$t_{f=max}$ (day)
DSA-150	67,53	35
AKP-4	113,77	21
5-ZL	123,25	48

The obtained results indicate that the lowest value of MTTF is for the DSA-150 pantograph, which may suggest its lowest durability. However, it should be taken into account that the calculated MTTF values refer to the theoretical mean value of time at which the failure may be observed, according to the approximation of Weibull distribution. Therefore, the more important information is the value of operation time at which the failure occurrence is the most probable. From the practical purposes such a value may indicate the actual durability of the pantograph. This approach may indicate the worst durability for the AKP-4 pantograph.

3.2 Data preparation for the Machine Learning

Reliability assesment and knowledge of experts allowed to prepare identification algorithms for technical condition and for replacement causes. The exemplary algorithms are shown below:

$$Wop = 1 \Leftrightarrow Nl_{i+1} = Nl_i \wedge (Top_{i+1} \neq Top_i \vee Nop_{i+1} \neq Nop_i) \qquad (2)$$

$$Wn = 1 \Leftrightarrow (Nl_{i+1} = Nl_i) \wedge (Top_{i+1} = Top_i) \wedge (Cop_i \neq 1) \wedge ((Gn1_i - Gn1_{i+1} < 0) \vee (Gn2_i - Gn2_{i+1} < 0)) \qquad (3)$$

$$N_1 = 1 \Leftrightarrow Nop = 1 \wedge N_3 = 0 \wedge (Gn1 < 32 \vee Gn2 < 32) \qquad (4)$$

$$N_2 = 1 \Leftrightarrow Nop = 1 \wedge (N_1 + N_3 = 0) \wedge ((Gn1 > 33) \vee (Gn2 > 33)) \qquad (5)$$

$$N_3 = 1 \Leftrightarrow Nop = 1 \wedge (|Gn1 - Gn2| \geq 2) \qquad (6)$$

Developed algoritms, in turn, allowed to prepare input data for machine learning. Learning data – predictors, are presented in Table 1.

Table 3. Machine Learning Predictors

Name	Symbol
Review number	i
A new measuring cycle	$Cnew$
The number of days since the replacement	D
The quarter of the year	Q
Current collector type	Top
Front / rear current collector	Cc
Difference in the N1 thickness between reviews	$Th1$
Difference in the N2 thickness between reviews	$Th2$
Earlier technical condition	S
The reason for the replacement	N

3.3 Prediction model

Machine learning is currently used in many fields. In the paper, the predicted model is based on the algorithms for the classification of machine learning. For the development of the predictive model, it was decided to use the MATLAB environment due to its strengths associated with machine learning.
It has a high quality function library. The algorithms are compliant with industry standards, allowing to reduce the time required to develop solutions to the minimum. The tools used to validate the model are embedded in the application, making the developed model to be easily evaluated.

In order to develop the best predictive model, the following methods were tested:
decision trees (Complex Tree, Medium Tree, Simple Tree), supporting vector machines (Linear SVM, Quadratic SVM, Cubic SVM, Fine Gaussian SVM, Medium Gaussian SVM, Coarse Gaussian SVM), methodic of nearest neighbors (Fine KNN, Medium KNN, Coarse KNN, Cosine KNN, Cubic KNN, Weighted KNN) or classifiers (Boosted Trees, Bagged Trees, Subspace Discriminant, Subspace KNN RUS Boosted Trees).

Among the methods of classifying machine learning, the method of decision trees proved to be the best. Below, Figure 5 presents a graphic representation of the Complex Tree model. The tree in this form reflects how the classification decisions were made on the basis of attributes.

In proposed model, the maximum number of splits was 100; it was applied Ginis Diversity Index as a split criterion, and there was none surrogate decision split.

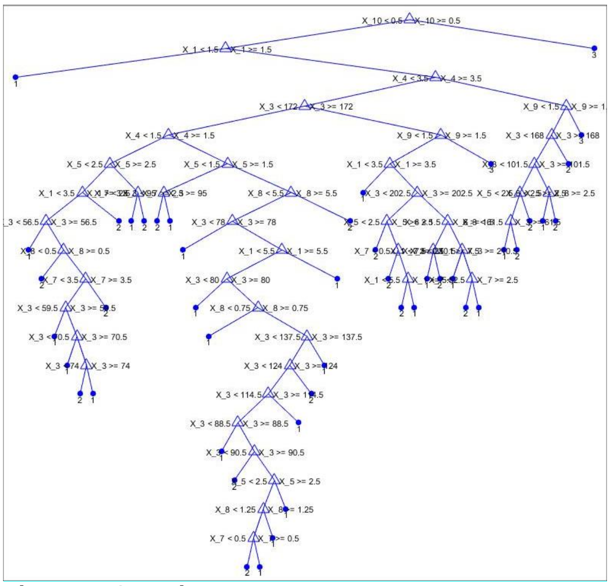

Figure 7. Complex Tree

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The analysis of errors in the assignment to different classes was made with the help of a confusion matrix. The matrix (3 × 3), where the lines correspond to the correct decision classes, and the columns with the decisions predicted by the classifier are shown in Figure 6. At the intersection of the row *i* and columns *j* is the number of examples originally belonging to the *i-th* class, and included in the *j*-class.

As it results from the evaluation of the developed model, the correctness of the classification is about 81%. However, the prediction of the damage itself is key to reducing the damage of the sliding strips. In the model it was defined as conditional technical condition (class 2). It means that in the next time interval it will be necessary to replace the sliding strip. The prediction of this state thus makes it possible to reduce damage to the overlays.

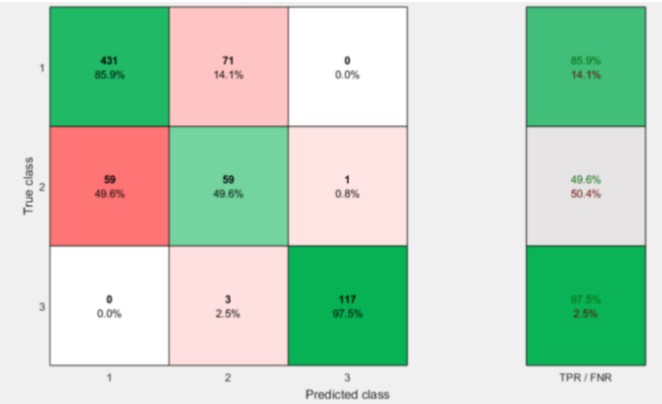

Figure 8. Confusion Matrix for Decision Tree

4. FAILURE ANALYSIS

Damage analysis included two variants. Variant I was based only on processed archival data. For the analysis of Variant II, data from technical reviews modified by the predictive model were used. The structure determined during the preliminary data processing in step 1 was also used in step II, thanks to which it was possible to compare the results.

Below, Figure 7 shows the correctness of the classification of technical states. The three technical states used mean as follows:

1 - possibility of further use,

2 - limited possibility of further use, it will be necessary to replace the overlay for the next inspection

3 - no use, it is necessary to replace the overlay

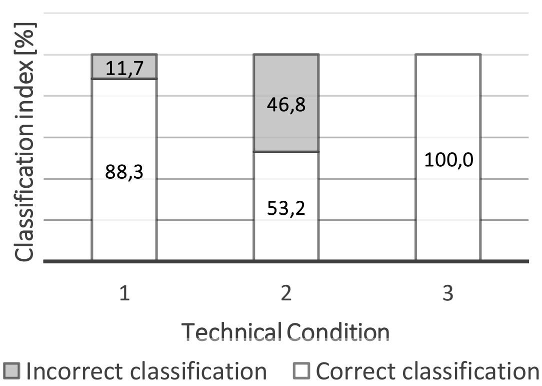

Figure 9. Correctness of classification of technical condition

Analyzing the data in variant I, there were 47 damages to the cap or to the collector. In variant II (after machine learning), only 23 were noted. The use of the presented model allows to reduce damage by about 50%.

5. CONCLUSION

In conclusion, the presented metodology is based on Artifitial Inteligence. Failure analysis is necessary for preparing the input data correctly for both the variants. Variant I concerns the analysis only of data obtained during the technical review, when variant II is based on the classification machine learning method, developed under this article.

Results show that predicion of a technical condition can reducesliding strip damages by about 50%. Therefore, the costs related to the repair of damaged railway infrastructure caused by the poor technical condition of the collector can be significantly reduced. The application of the developed method would also enable the reduction of railway delays caused by damage to the current collector system - the traction network. Further research will focus on the development of a predictive model that allows 100% prediction of damage so that its negative effects can be eliminated.

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