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Correlation Between the Main Diagnostic Features of Rail Vehicles' Wheel Profiles in the Operational Period

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Summary
The paper is dedicated to correlations between the main diagnostic features utilised for assessing the wear of wheel tyre running treads and the wear of wheel flanges. The paper focuses on analysis of the correlations between these features in the period between the mounting of new wheel tyres or new monoblock wheels in a given wheelset up to their replacement. The wheels of Electric Multiple Units and shunting locomotives were the objects of the research. The measurement data obtained from a domestic railway undertaking contain, however, many errors. It was noted that in some cases the measured values were put in the wrong places on the measurement cards. It is also possible that in some cases the wheel surfaces were not prepared properly for measurements. For those reasons, only some data, for which there were no doubts regarding credibility, were chosen. Those data were appropriate for determining the trend line equations, which depict an overview of how the values of the diagnostic features are correlated with each other. The obtained functions of the characteristics of the changes in the diagnostic features as well as calculated Pearson correlation coefficients show that there is a significant correlation between those features. This is not dependent on the significantly different operational conditions of the groups of tested rail vehicles. Conclusions on the existence of significant correlations between the tested features can be used for the creation of innovative solutions dedicated for wheel diagnostics of rail vehicles. This especially applies to the design of analytical functions, which could be used for real time verification of the correctness of the measurement results.

Keywords: operational tests, rail vehicles, diagnostic features, wheel profiles, Pearson's correlation coefficient

1. Introduction

The wear of wheels is a very important subject and has a close relationship with the safety of rail vehicle movements. This is reflected in the quantity of elaborations dedicated to the subject, conducted in Poland and abroad, like those shown in positions [1, 6–9] of the bibliography. This is also a reason why measurements of the main features of wheel profiles are performed systematically in the operational period covering: thickness of the wheel tyre (of the rim-tyre of the monoblock wheels) as well as thickness, height and shape of the wheel flange. Limit values for those features are defined in appropriate instructions (e.g. BT-11 issued by PKP InterCity in the year 2010 and in other documents [2–4]) enabling decisions to be taken about wheels reprofiling on the basis of current measurement results. The results of such measurements, collected in the appropriate databases, enable individual curves to be drawn representing changes in the values of the features describing the wear of the wheels, as well as averaged characteristics comprising all the wheels in a given vehicle or in a group of vehicles with similar on-going exploitation processes, for example. It is also possible to define functional relationships between the values of a given feature and the mileage of a vehicle. Such relationships were determined in [2] in relation to the thickness of the rim-tyre of the wheel and in [9] in relation to the thickness of the wheel tyre as well as in relation to the thickness, height and shape of the wheel flange.

From the epistemological point of view, it is interesting whether changes in the values of individual diagnostic features are correlated with each other. Preliminary analysis presented in [9] in relation to a defined group of electrical locomotives permit the assumption that it could be so also in the case of other types of rail vehicles. The objects of the research presented in this article were the wheels of Electrical Multiple Units (EMU) and of shunting locomotives. These

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vehicles are utilized in significantly different circumstances, and therefore positive verification of the thesis regarding correlation between changes in the main diagnostic features of wheel profiles can be treated as an important rule while assessing wheels wear.

2. Characteristics of the research objects

The characteristics of the research objects have to take into account not only determination of the substantive features of the objects, but also determination of the exploitation conditions. Out of the diagnostic features of the wheelsets having wheels with tyres and monoblock wheels (without tyres), the following diagnostic features, according to [6], belong to the main ones:

- thickness of the wheel tyre *O* or of the rim-tyre of the wheel *W*,
- thickness of the wheel flange O_g,
- height of the wheel flange O_w,
- shape of the wheel flange q_R.

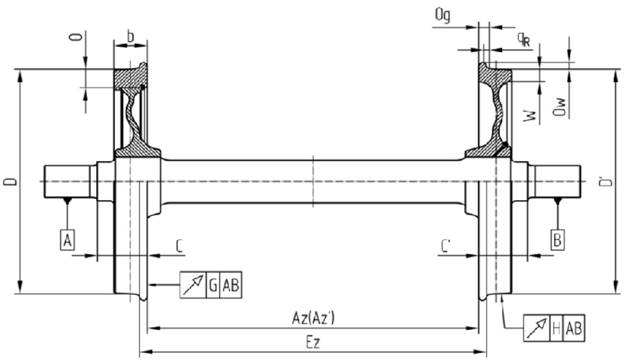
The way to measure these features is defined in the Instruction [5]. An overview is shown in Figure 1. In the case of the thickness of the wheel tyre or of the rim-tyre of the wheel the result is an average of three measurements carried out in planes going through the middle of the wheel and having a 120° angle between each other. This feature can be measured with a slide calliper or ultrasonic measuring device.

The Instruction [5] does not define planes for other measurements of the main diagnostic features of wheel profiles. As a result, a single measurement carried out with a slide calliper or electronic device can be accepted as reliable. It should be added that the thickness of the wheel flange of a given wheel is one of the components of the secondary diagnostic feature, which is the sum of the thicknesses of the wheel flanges in a given wheelset. This secondary feature, in this case, cannot be taken into account in correlation analysis as it would relate to primary features of two different wheels of the wheelset.

It was decided, for the purpose of this elaboration, that the wheels of Electrical Multiple Units and the wheels of shunting locomotives will form the objects of the research. Appropriate values describing the diagnostic features of the wheel profiles were collected from the measurement cards of two groups of vehicles: ED74 Electric Multiple Units and SM42 shunting locomotives.

An Electric Multiple Unit of the ED74 type is a vehicle dedicated for long distance passenger transport with a maximum speed of 160 km/h [7]. [4]. The vehicle consists of four units supported by five two-axle bogies via intermediate pneumatic springs connected to bogie frames. Two 22MNk type bogies put at the ends of the EMU are motor bogies with the wheel arrangement B_0', while three 37ANk type middle trailer bogiesare Jacobs bogies shared by neighbouring units. The first suspension level is composed of rubber-metal elements, while the second consists of pneumatic springs. Propulsion is ensured by four asynchronous engines of the TMF 59-39-4 type with a cumulative power of 2000 kW. Driving gear is ensured by an axle gear of the SZH 595 type. The vehicle is equipped with an electro-dynamic brake and friction disc brakes put on all wheelsets. Braking discs are fixed to the side surfaces of the wheels. Wheelsets comprise monoblock wheels with a construction diameter of 840 mm. The minimum limit diameter for the wheels equals 790 mm. Construction thickness of the rim-tyre of the monoblock wheel equals 55 mm, while the limit value equals 30 mm. ED74 EMUs are utilized mainly on the Cracow – Warsaw – Terespol routes, which are characterised by the very good technical state of the tracks.

wheels with the wheel tyres[1)] monoblock wheels (without tyres)[1)]



[1)] All symbols representing parameters, except symbols 0, D1 and W, are the same for monoblock wheels (without tyres) and for wheels with the tyres

Fig. 1. Diagnostic features of the wheelsets with tyred wheels or monoblock wheels [5]

A diesel locomotive of the SM42 type is a locomotive prepared for shunting with the wheel arrangement B_0' B_0'. The maximum vehicle speed is 90 km/h [2, 3]. The locomotive is supported by two identical driving bogies of the 1LN, 1LNa type. Propulsion units are fixed to the bogie frames together with guides and braking system elements (braking cylinders and rods). The vehicle has two levels of suspension: a suspension between wheelsets and bogie frame ensured by leaf springs and rubber elements, as well as a suspension between the bogie frame and vehicle underframe ensured by coil springs. The locomotive has a diesel engine of the a8C22 type with 800 KM power (6D series locomotive) or a diesel engine of the C-18 type with 765 KM (18D series locomotive). Driving gear from traction engines of the LSa-430 type to the wheelsets is ensured by a toothed gear. Wheelsets comprise tyred wheels with a 1100 mm construction diameter for which the minimum limit diameter equals 1010 mm. Construction thickness of the wheel tyre is 75 mm, while the limit value equals 30 mm. The locomotive is equipped with an Oerlikon type pneumatic brake. Braking takes place by tight pressing of cast iron friction elements (braking shoes) to the wheelset running treads. The locomotives chosen for research were utilized on shunting yards in Cracow and Katowice for shunting operations dedicated for the forming of wagons sets for the trains. It should be added that the technical state of tracks should be recognized generally as bad.

3. Input data

There was an attempt to prove the thesis that there is a correlation between changes in the main wheels diagnostic features based on original paper measurement cards (inspection notes) of the chosen individual ED74 Electric Multiple Units and SM42 shunting locomotives. These cards reflected certain periods of exploitation of these vehicles, as shown in Table 1.

Table 1

List of vehicles covered by research

Vehicle type	Alternative number	Limit dates	
		from	to
ED74	*xx*1	02-10-2015	26-02-2018
	*xx*2	06-07-2016	13-02-2018
	*xx*3	18-06-2016	06-03-2018
SM42	*mm*1	12-03-2015	05-03-2018
	*mmm*3	09-06-2016	26-02-2018

[Own study].

The shunting locomotive *mm*1 is a standard SM42 type locomotive, while *mmm*3 is a locomotive of the same type after modernization.

Data from measurement cards were re-written into specially prepared Excel sheets, enabling presentation of the changes in individual values of the diagnostic features in an orderly and clear manner (as a sequence of values of the same feature). Example fragments of such connotations are shown in Tables 2 and 3. Due to the different numbers of wheelsets in both types of vehicles, different forms of data sheets were used. It should be added that the measurement cards of the ED74 EMUs do not contain data about wheels wear represented by the change in the thickness of the rim-tyre of the wheel. This is a result of the lack of an appropriately adapted measuring device. Verification of this thickness, which is required on the basis of regulations, is performed by visual checking of the location of the edge of the wheel tyre running treads on the outer side in relation to the groove indicating the maximum allowed wear of the wheel rim-tyre. The measured values of individual diagnostic features, which are re-written to defined data sheets using italics, represent dimensions after reprofiling of the wheel profile.

Arrangement of the columns of the measured values shown in Tables 2 and 3 enables easy tracking of the changes in individual diagnostic features during exploitation periods. Closer analysis of these data leads to, however, some doubts about:

- whether the thickness of the wheel tyre measurements of the SM42 type locomotives were conducted with appropriate care,
- whether the results reflect an average based on three measurements,
- whether the data written down on the card are related to the appropriate wheel,
- whether the operational correctness of the non-manual measuring devices were checked,
- whether the places on the wheel surface, which were used for measurements, were correctly prepared.

The first issue is a direct consequence of the fact that, in a few cases, the values reported by measurement cards show that the thickness of the wheel tyre increases during exploitation of the SM42 shunting locomotives. The changes are sometimes higher than 1 mm. This could reflect ovalization of the wheels if thickness measurements were not performed in three places and average values were not calculated. It could also reflect incorrect measurements or incorrect data registering.

Doubts can also arise as to whether the measured values were associated with appropriate wheels. Analysis of the data represented by sequences of changes in the values of individual wheels leads to the statement that the exchange of values between wheels ensures values which are credible, proven during consecutive measurements performed one after another. It should be added that the person writing data on the original measurement cards may not have easy or current access to previous measurement results. This does not support self-control while measurements are performed, namely it does not support decision-taking about the re-testing of an individual diagnostic feature or change in place where the measurement results are being recorded.

An important issue, in relation to the assessment of the credibility of records in the tested vehicles' wheel measurement cards, is the appropriateness of the operation of electronic measuring devices, i.e. ultrasonic thickness gauges and laser profilometers. Each measurement result which diverges from values arising from the expected trend of changes in a given feature should be treated as a signal triggering correctness checking of

Table 2

Fragment of the ED74 type Electric Multiple Units data sheet

Maintenance level for Emu ED74-*xx*1				wheelset 1						wheelset 2					
P2		[km]		wheel R			wheel L			weel R			weel L		
Date	No of days	mileage	run	Ow	Og	qr	Ow	Og	qr	Ow	Og	qr	Ow	Og	qr
2015-10-02	–31	964643	0	30.60	31.51	9.87	29.88	28.45	9.21	29.81	31.65	9.02	30.09	29.50	10.50
2015-11-02	31	976462	11819	30.20	31.40	9.80	30.50	28.50	9.20	31.30	30.60	9.00	30.60	29.20	9.80
2015-11-29	27	983503	7041	30.60	31.47	9.61	30.10	28.13	8.98	30.95	30.39	8.84	30.17	29.24	9.69
2015-12-29	30	995576	12073	30.24	31.56	9.71	30.22	28.09	8.86	31.14	30.27	8.84	30.38	29.33	9.69
2016-01-25	27	1012490	16914	30.60	31.50	10.10	30.30	28.30	10.20	31.90	30.20	9.30	30.60	29.30	9.80
2016-02-22	28	1026975	14485	*27.20*	*31.20*	*8.30*	*27.20*	*31.20*	*8.30*	*27.20*	*30.00*	*8.40*	*27.70*	*29.60*	*8.90*
2016-03-06	13	1041251	14276	27.30	31.10	8.00	27.40	28.10	8.20	27.40	30.40	8.30	27.90	29.50	8.50

[Own study].

Table 3

Fragment of the SM42 type diesel locomotive data sheet

Lokomotive SM42-3*mmm*				bogie															
Maintenance level				ZK 1								ZK 2							
P2		[km]		KP1 [mm]				KL1 [mm]				KP2 [mm]				KL2 [mm]			
Date	No of days	mileage	run	O	O_w	O_g	q_r	O	O_w	O_g	q_r	O	O_w	O_g	q_r	O	O_w	O_g	q_r
2016-06-09	42498	35179	0	72.30	28.20	32.20	10.40	72.40	28.20	32.20	10.20	71.90	28.20	32.20	10.40	72.00	28.30	32.30	10.00
2016-07-12	33	37292	2113	72.60	28.60	32.20	10.40	72.40	28.20	32.00	10.00	72.60	28.50	32.00	10.20	72.00	29.00	32.30	10.60
2016-08-09	28	39005	1713	72.70	28.42	32.08	10.17	72.50	28.41	31.74	9.97	71.80	28.37	32.02	10.17	71.90	28.40	32.34	9.82
2016-09-08	30	40549	1544	73.10	28.20	31.80	9.60	72.70	28.20	31.50	10.30	72.20	28.40	31.80	10.30	73.20	28.10	31.60	10.20
2016-10-07	29	42150	1601	72.10	28.80	32.00	10.20	71.90	29.00	32.00	10.00	71.40	29.00	32.00	10.00	71.90	28.80	32.00	10.00
2016-11-04	28	44010	1860	71.80	28.70	32.00	10.00	71.90	29.00	31.80	10.00	72.00	29.00	32.00	10.20	71.50	28.50	32.20	10.00
2016-12-05	31	46361	2351	72.30	28.90	31.50	9.80	72.40	28.90	30.80	10.50	72.60	29.10	31.20	10.50	72.40	29.00	31.20	10.30
2017-01-03	29	47869	1508	71.90	29.00	31.50	10.00	72.00	29.40	30.80	10.20	71.50	29.20	32.00	10.20	71.60	29.70	31.50	9.60
2017-02-02	30	48238	369	72.00	29.00	31.00	10.30	72.10	29.50	31.50	10.50	71.20	29.00	31.50	10.50	71.50	29.50	31.50	10.00
2017-03-03	29	49142	904	72.30	28.60	31.90	9.40	72.20	28.40	31.20	10.00	71.80	28.70	31.50	10.10	72.10	28.60	31.50	10.00
2017-06-14	103	49425	283	*70.30*	*28.00*	*32.00*	*9.00*	*71.30*	*28.00*	*32.00*	*10.00*	*70.80*	*28.00*	*32.00*	*9.50*	*70.50*	*28.00*	*32.00*	*10.00*
2017-07-14	30	49747	322	72.00	28.00	31.00	9.20	71.00	28.00	31.20	10.50	71.00	28.00	31.20	9.50	71.00	28.00	31.21	10.00

[Own study].

the operation of such measuring devices, after excluding all other possible sources of errors.

Errors could also be caused by inappropriate preparation of the wheel surfaces for tests. Places in which measurements are performed should be carefully cleared and should omit places with flat spots and/or built-up treads and places where such defects were provisionally removed from the surface.

4. Correlation analysis

Difficulties associated with obtaining reliable data on all the results of measurements of the main diagnostic features of wheelset sets meant that for further tests only those records were selected that met the appropriately used out weak relationships between the diagnostic features obtained in successive measurements:

$$w_{c1}(t) \le w_{c1}(t+1) \vee w_{c2}(t) \le w_{c2}(t+1) \quad (1)$$

where:

w_{c1}, w_{c2} – values of individual diagnostic features,
t – identifier of the next measurement.

The periods out of which data sets were taken for individual locomotives are shown in Table 4.

Table 4

Data ranges used for the analysis

Vehicle type	Alternative number	Limit dates	
		from	to
ED74	*xx*1	22-09-2016	28-12-2016
	*xx*2	27-11-2016	05-03-2017
	*xx*3	28-10-2016	24-01-2017
SM42	*mm*1	06-09-2017	05-03-2018
	3*mmm*	08-09-2016	05-12-2016

[Own study].

It is possible to draw functions reflecting changes in the values of individual features on the basis of the data taken from reference periods defined in Table 4. It is also possible to show how these changes are correlated with each other by analysing pairs of the features.

The functions shown in Figure 2 represent, for example, changes in the shape of the wheel flange in relation to the thickness of the wheel flange. This specific relationship, taking into account common data regarding the left and right wheels, could be approximated to a linear function described by the following formula:

$$y = 1.4872x - 37.129 \text{ mm} \quad (2)$$

It is possible to calculate correlation coefficients taking into account data from the reference periods. Pearson correlation coefficients, understood as changes in the diagnostic features of the wheel profiles related to individual combinations of two analysed diagnostic features, are shown below (Tables 5–9). The thickness of the wheel tyre of shunting locomotives is omitted because in the case of Electric Multiple Units measurement documentations do not contain values referring to the thickness of the rim-tyre of the monoblock wheels.

Table 5

Correlation coefficients – locomotive SM42_3*mmm*

Locomotive SM42_3*mmm*, wheelset 3					
Right wheel			Left wheel		
O_w and O_g	O_w and q_r	q_r and O_g	O_w and O_g	O_w and q_r	q_r and O_g
–0.81	-0.90	0.96	–0.88	–0.82	0.92
Average					
O_w and O_g		O_w and q_r		q_r and O_g	
–0.85		–0.86		0.94	

[Own study].

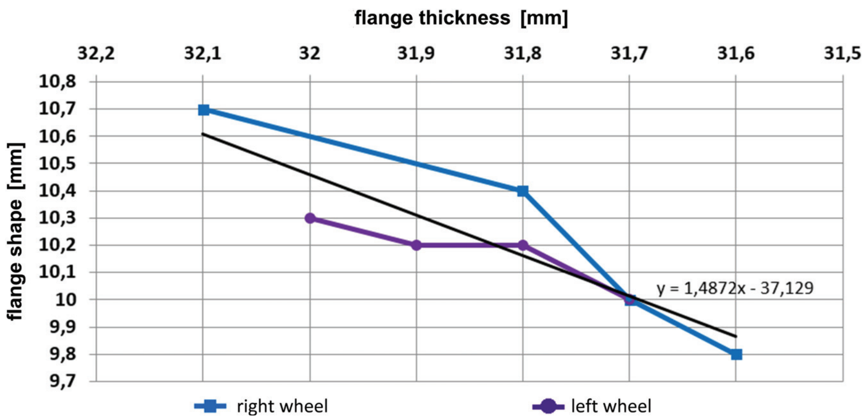


Fig. 2. Chosen example of the changes in the shape of the wheel flange in relation to the thickness of the wheel flange [own study]

The correlation coefficients shown in Table 5 denote that there is a strong correlation between changes in the thickness, shape and height of the wheel flange. This comes from the fact that absolute values of the coefficients are in a range from 0.81 to 0.96. The highest value refers to changes in the shape and thickness of the wheel flange, while the lowest value refers to the changes in the thickness and height of the wheel flange. Negative values of the coefficients in individual combinations mean that:

- a decrease in the thickness of the wheel flange O_g is associated with an increase in the height of the wheel flange O_w,
- a decrease in the shape of the wheel flange q_r is associated with an increase in the height of the wheel flange O_w.

The positive values of the correlation coefficients in Table 5 refers to the interdependence of the thickness and shape of the wheel flange. A decrease in the value of one dimension is associated with a decrease in the other. The presence of a similarly strong correlation is also proven by the results presented in Tables 6–9.

Table 6

Correlation coefficients – locomotive SM42_*mm*1

Locomotive SM42_*mm*1, wheelset 1					
Right wheel			Left wheel		
O_w and O_g	O_w and q_r	q_r and O_g	O_w and O_g	O_w and q_r	q_r and O_g
–0.94	–0.97	0.97	–0.89	-0.86	0.99
Average					
O_w and O_g		O_w and q_r		q_r and O_g	
–0.91		–0.92		0.98	

[Own study].

Table 7

Correlation coefficients – EMU ED74_*xx*1

EMU ED74_*xx*1, wheelset 8					
Right wheel			Left wheel		
O_w and O_g	O_w and q_r	q_r and O_g	O_w and O_g	O_w and q_r	q_r and O_g
–0.94	–0.91	0.92	–0.89	–0.89	0.89
Average					
O_w and O_g		O_w and q_r		q_r and O_g	
–0.91		–0.90		0.91	

[Own study].

Table 8

Correlation coefficients – EMU ED74_*xx*2

EMU ED74_*xx*2, wheelset 7					
Right wheel			Left wheel		
O_w and O_g	O_w and q_r	q_r and O_g	O_w and O_g	O_w and q_r	q_r and O_g
–0.97	–0.92	0.98	–0.80	–0.96	0.91
Average					
O_w and O_g		O_w and q_r		q_r and O_g	
–0.88		–0.94		0.95	

[Own study].

Table 9

Correlation coefficients – EMU ED74_*xx*3

EMU ED74_*xx*3, wheelset 8					
Right wheel			Left wheel		
O_w and O_g	O_w and q_r	q_r and O_g	O_w and O_g	O_w and q_r	q_r and O_g
–0.83	-0.87	0.82	–0.87	–0.83	0.95
Average					
O_w and O_g		O_w and q_r		q_r and O_g	
–0.85		–0.85		0.88	

[Own study].

Individual correlation coefficients, depending on the vehicle type, belong to the ranges shown in Table 10. The differences, which are presented in this table, are not significant and do not provide a basis for further deductions regarding, among others, the influence of the suspension construction, of the character of the traction work, and of the technical state of the tracks onto values of those coefficients. However, they do provide a basis for the formulation of a postulate regarding the possible use of those relationships to create a data computing based system for monitoring correctness of the measurements of the main diagnostic features of the wheel profiles.

Table 10

Ranges of the calculated correlation coefficients

Vehicle type	**O_w and O_g**		**O_w and q_r**		**q_r and O_g**	
	min	**max**	**min**	**max**	**min**	**max**
Locomotive SM42	–0.81	–0.94	–0.82	–0.97	0.92	0.97
EMU ED74	–0.8	–0.97	–0.87	–0.96	0.82	0.98

[Own study].

5. Summary

There is one fundamental obstacle preventing the goal of elaboration, understood as proving the existence of a strong correlation between the main diagnostic features of the wheels of rail vehicles. This is existing data credibility arising from the existing system used to register the results of measurements of those features. As already mentioned above, the arrangement of places on the measurement cards, onto which staff responsible for diagnostics put values from consecutive measurements, does not support tracking of the changes in those values. It is focused on qualification whether the value of a given feature fits in the permissible range or not. When the result of qualification is positive, the measured value could be put on the card in a place not necessarily dedicated to the wheel on the same side as during previous measurements. Such a supposition comes from the collected documentation with measurement results.

Other mistakes could also arise from the incorrect operation of the electronic measurement devices and insufficient preparation of the surfaces for the tests. The possible occurrence of such incidents leads to the following conclusion; it is necessary to construct a data computing based system supporting real time, which would enable monitoring of the correctness of the way measurements are performed and how results are recorded. It is possible to utilize correlations which define trends in changes in the values of the main diagnostic features of the wheel, as well as correlations of the changes in those features expressed by Pearson correlation coefficients. Those trends and correlations could be provisionally defined on the basis of analysis of existing fragments of the measurement documentation available for defined types of vehicles – fragments which do not cause doubts regarding the credibility of recorded data.

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