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APPLICATION OF THE SELECTED MULTICRITERIAL PROGRAMMING METHOD IN THE MANAGEMENT OF RAIL VEHICLE BOGIES IN ORDER TO EXTEND THE SERVICE LIFE OF BRAKE DISCS

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Abstract

The wheel set of a rail vehicle with a disc brake is the basic assembly of a rail vehicle exposed to abrasive wear. From the operational point of view, the wear process of the wheels and brake discs is uneven, which for the carrier involves switching off the vehicle, once when the maximum wear of the discs is reached and again when the wheels wear out. The process of both untying the wheel set from the bogie, dismantling the wheels and discs from the axle is a time-consuming and expensive process, which consequently affects the exclusion of the vehicle from planned traffic. In the article on the basis of brake disc wear results, 3 concepts of bogie management were proposed. The first concerns the bogie rotation, the second and third concepts concern the exchange of bogies with and without rotation. Using the MUZ multi-criteria programming method, the concepts were evaluated and the best one was selected taking into account the evaluation criteria. The aim of the article is to present concepts that reduce the wear of discs brake systems in a multi-unit traction unit using bogie migration under the vehicle.

Keywords: wheelset, brake disc, abrasive wear, management, multi-criteria programming

List of Symbols/Acronyms

WA – vibroacoustic signal;
FFT – Fast Fourier Transform;
MUZ – Zeroed Unitarization Method;
FC – Objective function;
ELF – Electric Low Floor;
EN – electric multiple unit for local traffic;
DSU – Maintenance System Documentation;
Z1 NP – right disc of drive wheelset No. 1;
Z1 NL – left disc of drive wheelset No. 1;
Z3 TP – right disc of rolling wheelset No. 3;
Z3 TL – left disc of rolling wheelset No. 3;
Zi – brake disc wear [mm];
Ti – brake disc rolling value [mm];
P2 – periodic inspection;
P4 – revision repair;
Qi – value of the aggregate variable;
D – diameter of the wheel in the rolling circle [mm];
T – width of brake discs [mm];
tu – time of use of brake discs [days];
pm – mileage of the vehicle [km].

1. INTRODUCTION

A wheelset with brake discs is the basic unit of every rail vehicle responsible for tracking in the railway track and braking [18, 23]. Due to the fact that modern vehicles are built with various pneumatic, mechanical or electrical devices on the vehicle chassis, brake discs are mounted directly to the wheels [1], as shown in Figure 1a) in contrast to the old type of rail vehicles (Fig. 1b).

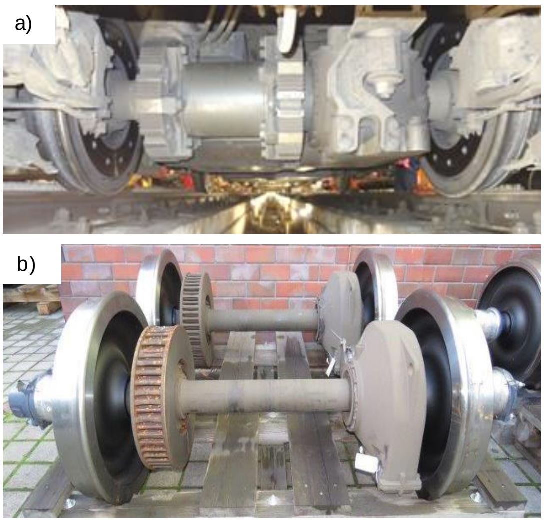

Fig. 1. View of a driven wheelset in: a) modern, b) in a classic multiple unit [fot. A.M. Rilo Cañás]

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From the diagnostic point of view, i.e. the assessment of the condition of the disc brake, both in new and older vehicles, it is necessary to enter under the vehicle into the inspection pit between the rails. In modern vehicles, the mounting of brake discs on the wheel only allows observation from the outside of the vehicle to the technical condition of only the external discs. In the case of assessing the wear of friction linings or discs between the wheels, it is also necessary to go under the vehicle [19].

Disc brake diagnostics is used to assess the technical condition of brake discs and friction linings [4]. In the case of discs, linear wear is determined on its thickness and the friction surface is assessed for the presence of defects such as chipping or microcracks, as shown in Figure 2 [27]. In the case of friction linings, diagnostics is carried out in order to determine the actual thickness and to prevent the permissible linear wear from exceeding [5, 24]. In automotive and railway practice and technology, diagnostics are only (if any) used to assess the condition of friction linings than brake discs, which wear more slowly [11, 30].

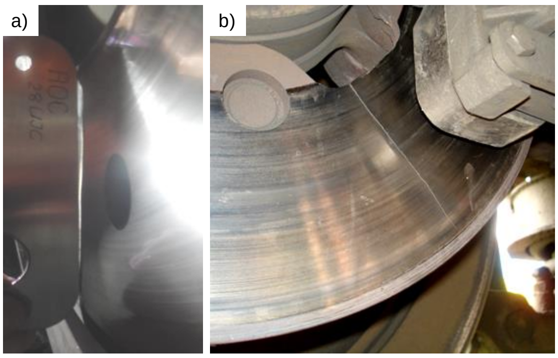

Fig. 2. View of brake discs with: a) linear wear, b) radial crack [fot. W. Sawczuk]

In automotive and railway technology, diagnostics of the braking system is carried out using available mechanical and electrical solutions [12, 22]. Mechanical systems include acoustic plates [7] attached to the friction lining, which at the limit wear of the friction linings (about 2 mm) begin to vibrate when they come into contact with the rotating disc. This consequently generates a squeaking sound audible to both the driver and other users. This is the most commonly used solution in motor vehicles. In some trucks and buses, there is an indicator of wear of friction linings in the form of a protruding pin (rod) from the brake caliper [10]. In the case of new friction linings, the rod is extended, while in the case of completely worn linings, the pin is retracted in the clamp [6]. This solution is less popular, as it requires the driver to visually check the periodic state of the rod insertion at a standstill. In the field of electrical equipment, the most advanced solution is an electric sensor, which in the event of extreme wear of the lining contacts the brake disc, closing the electrical circuit, thanks to which the car driver receives information on the panel about the need to replace the linings [26]. The electric sensor solution led to its further development and the Brake Monitor BW 03 [3] system with three sensors placed on different friction lining thicknesses. The first sensor generates a signal and the green light of the indicator light with the correct thickness of the lining, the illumination of the yellow light from the second sensor indicates the permissible wear of the linings, while the illumination of the red light indicates the limit permissible wear of the linings and the need for absolute replacement [29].

In disc brake systems of rail and railway vehicles, in the assessment of the technical condition of brake discs in accordance with works [13, 31], the axial run-out measurement is also performed. In the case of brake discs of motor vehicles, values exceeding 0.05 mm are not permissible, while in railway vehicles 0.25 mm [8].

In the diagnostics of braking systems, it is also worth mentioning the work in the field of vision diagnostic systems occurring on the vehicle and in the railway infrastructure.

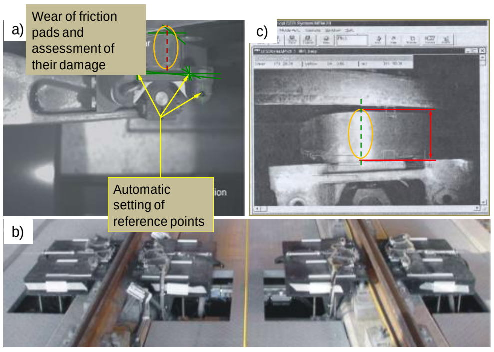

Fig. 3. a), b) View and principle of operation of the underfloor post for photographic assessment of friction linings wear c) HARD soft vision system [2]

In the first case, a camera was mounted behind the brake caliper, which recorded the image of the disc and friction linings. After processing the above-mentioned images from different periods, the actual thickness of the brake linings and the brake disc was calculated in an appropriate computer program [2]. This system has not been used in practice after positive tests. On the other hand, a vision system mounted in the railway track was implemented with great success, which recorded images from each wheelset axis during the passage of the train and calculated the actual thickness of the friction linings of the disc brake. The system also worked in two states and I send information about the permissible and limit wear of friction linings [15]. In the field of railway infrastructure, it is also worth mentioning another diagnostic system, ASDEK [16], which uses thermal detectors to measure the temperature of the braking system during the passage of a train. In this way, the correct operation of the brake in the range of the brake on and off is checked. The brakes should be turned off while driving. The system registers the temperature from each brake disc and brake pad on all wagons and sends two messages. The first signal with an increased temperature as a warning and the second signal as an alarm and stop signal for an absolute stop of the train. Then the driver stops the train and, in the presence of a railway auditor, checks the cause of the wagon running with the brake on [28].

In the field of disc brake diagnostics, many researchers also conducted research on a vibroacoustic system for assessing the wear of friction linings. In the works [14], a successful attempt was made to assess the condition of the brake by measuring the acceleration of vibrations of the friction linings during the braking of the train. Analyses of WA signals were carried out in the time, amplitude and frequency domains. The highest accuracy of estimating the thickness of friction linings was obtained by analyzing the wear from selected frequency bands using the FFT method [25].

2. METHODOLOGY AND OBJECT OF RESEARCH

The object of the main tests were EN76 ELF electric multiple units (Fig. 4) manufactured by the PESA Rail Vehicles factory in Bydgoszcz [21].

Fig. 4. View of the 22WE (EN76) vehicle during the exit from the Poznań Główny station [fot. A.M. Rilo Cañás]

The research was conducted for a period of about 5 years (from 2012 to 2018) until the first P4 level review, i.e. revision repair. During the P2 inspection tests, the width (thickness) of the T brake discs was recorded every 2 months according to Figure 5.b.

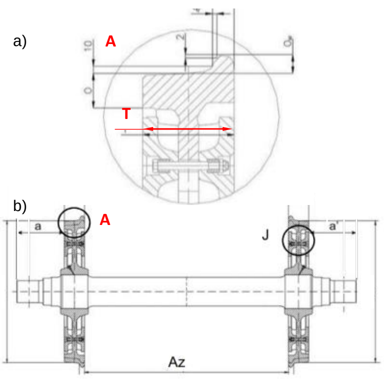

Fig. 5. Cross-section: a) a section of the wheel with discs mounted on both sides of the wheel centre, b) a rolling wheelset with the parameters checked during the P2 inspection [23]

The new brake discs, when mounted to the wheel, are characterized by a width of T=135 mm, the maximum permissible wear of the brake discs (10 mm) translates into a width of T'=125 mm. This dimension in operation cannot be exceeded. The legitimacy of diagnostics of brake discs than railway wheels results from the greater intensity of wear of the discs than of wheels to the limit (maximum wear). The first analysis of the results in terms of the maximum and minimum dimensions recorded during the P2 inspections of the vehicle showed that during the 5 years of operation of the group of vehicles, i.e. EN76 ELF electric multiple units, in each case or several discs reached maximum wear or were very close to achieving maximum wear. On the other hand, the railway wheels still had a large supply of material to allow them to continue their journey, as shown in Figure 6. Due to the fact that the discs are mounted on the railway (as shown in Figures 1a) and 5), it is necessary to take the vehicle out of service and remove the wheelsets only to replace the brake discs.

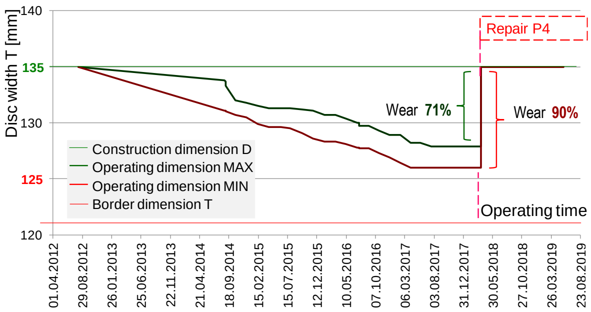

Fig. 6. Dependence: width of the brake disc from the time of operation, observed during P2 inspections until P4 repair

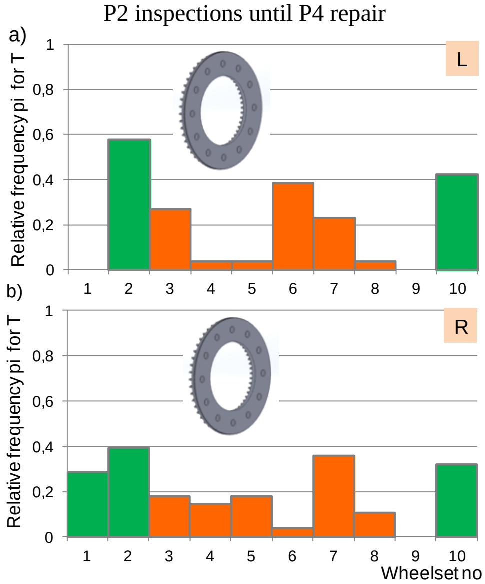

Fig. 7. Distribution of the relative frequency of the max (light green) and min (orange) dimensions: a) width of left brake discs, b) width of brake discs of right wheel sets during P2 inspections for the EN7 vehicle

Figure 7 graphically shows the distribution series with the number and relative frequency of the maximum and minimum dimensions of the brake disc widths on all wheelsets. Orange indicates the minimum dimension and light green indicates the maximum dimension of the T-width of the brake discs. The lack of a bar on the diagram next to a given wheelset indicated that this wheelset had never reached the maximum and min width T in relation to the other wheelsets during the P2 inspection.

Analyzing Figure 7, it is found that despite the fact that one of the brake discs reaches a dimension close to the border, the process of their wear is uneven. The outer castors numbered 1, 2, 9 and 10 have brake discs that wear very slowly compared to the middle castors (3 to 8). The end sets are mounted on the first and last bogies, which are drive bogies in relation to the middle rolling bogies. The slow wear of the discs on the drive bogies is due to the implementation of electrodynamic braking (engine braking in generator mode), so that the friction brake is rarely applied. On the rolling center bogies, there is only friction brake braking.

3. TROLLEY MANAGEMENT CONCEPTS

The issue of bogie management in electric multiple units results from the objective function, i.e. maximum extension of the time of use t_u of sets with brake discs attached, which is shown by the relationship (1). The extended time will also affect the longer mileage of the p_m vehicle.

$$FC = (max)\ t_u\ (T) \cap (max)\ p_m\ (T) \qquad (1)$$

where: FC – objective function,
t_u – time of use of the vehicle with brake discs,
p_m – mileage of the vehicle in kilometers,
T – brake disc width.

Obtaining a longer mileage of the vehicle and the time of use, with uneven wear of brake discs on all wheelsets, will be associated with the more expensive procedure of moving bogies from places on the vehicle where the greatest wear of discs occurs to those places under the vehicle where the said wear is the least. Thanks to this procedure, the time and mileage of the vehicle on the set, which has been characterized by the highest wear intensity since the beginning of operation, will be extended. This will also affect the accelerated wear on the set, which has had the slowest wear of the discs over time since the beginning of operation. From the technical point of view, this is not a disadvantage of the method of managing (repositioning) bogies or wheelsets, because during the revision repair after a period of 5 or 6 years (depending on the type of vehicle), all wheelsets are replaced with new ones in order to maintain similar wheel diameters. According to the documentation of the DSU maintenance system, it is unacceptable for a multi-unit rail vehicle such as a multiple unit to be used with wheels of different diameters [9].

For further analysis, as shown in Figure 8, the following concepts of railway bogie management are proposed:

- rotation of bogies or exchange of wheelsets within one bogie,
- Trolley migration without turning,
- Trolley migration with simultaneous rotation.

The first concept assumes that the wheel sets can only be swapped in the same bogie (trailer or drive). If the bogie design is symmetrical, this concept can also be called the concept of 180° rotation of the bogie under the vehicle. The second bogie management concept assumes that the bogie with the most worn wheelsets is dismantled under the vehicle and rolled to a place under the vehicle where the wheelsets have the least wear. In this concept, the bogie cannot be rotated. The first and second concepts are the least labor-intensive. The third concept assumes that the bogie can also be rotated so that the wheelsets can change their location from the front to the rear and the bogie changes its position under the vehicle. The bogie swap and their rotation are performed to move the wheelsets from the locations with the greatest wear to the places with the least wear of the wheelsets with brake discs. The third concept allows more variants of wheel set adjustments but is also the most labor-intensive.

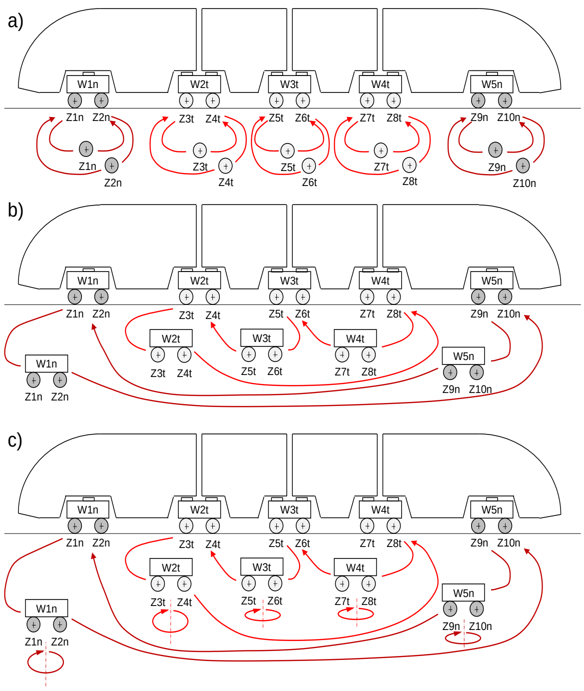

Fig. 8. Concepts for managing railway bogies: a) bogie rotation, b) bogie migration without turning, c) bogie migration with turning, W1n, W5n - first and fifth driving trolley, W2t, W3t and W4t - second, third and fourth rolling trolley

In order to improve (increase) the minimum width of the brake discs, it was decided to have 5 intervals for the replacement of bogie sets, according to the data contained in Table 1.

Table 1. Values of the summed wear of brake discs between P2 inspections and turning of the disc profile together with the values of the thickness of the cut layer for individual discs of the EN76 multiple unit

	$Z_{1\text{-}6}$	$Z_{\text{-}12}$	T_1	$Z_{\text{-}19}$	$Z_{\text{-}25}$	T_2	$Z_{\text{-}29}$	$Z_{\text{-}33}$
Z1NP	0.6	2.2	0.2	1.4	1.5	0.2	1.2	1.3
Z1NL	0.6	1.7	0.2	1.6	1.7	0.2	0.9	1
Z2NP	0.6	1.7	0.2	1.2	1.3	0.1	1.1	1.2
Z2NL	0.6	2.2	0.2	1.3	1.4	0.1	1.2	1.2
Z3TP	0.8	3.1	0.1	1.5	1.7	0	1.1	1.3
Z3TL	0.7	2.4	0.1	1.5	1.6	0	1.5	1.7
Z4TP	0.5	2.1	0.4	1.8	1.9	0.4	1.1	1.2
Z4TL	0.7	1.9	0.4	1.8	1.9	0.2	0.9	1.1
Z5TP	0.6	2.5	0.2	1.4	1.6	0.3	0.8	1
Z5TL	0.4	1.4	0.2	1.6	1.8	0.3	1.3	1.4
Z6TP	0.7	0.2	0.1	0.6	1.8	0.1	1.4	1.4
Z6TL	0.6	1.7	0.1	1.8	2	0.1	0.9	1
Z7TP	0.7	2.9	0.4	1.4	1.6	0.1	1.3	1.3
Z7TL	0.8	2.4	0.4	1.7	1.9	0.4	0.8	0.8
Z8TP	0.6	1.5	0.1	1.8	1.9	0.2	1.2	1.3
Z8TL	0.6	2	0.1	1.7	1.8	0.2	0.7	0.9
Z9NP	0.4	0.9	0.2	1.7	1.8	0.1	1.7	1.7
Z9NL	0.6	1.7	0.2	1.6	1.8	0.1	0,9	1
Z10NP	0.5	1.9	0.1	1.5	1.7	0.1	1.2	1.2
Z10NL	0.6	1.8	0.1	1.4	1.5	0.1	1	1.1

Z1 NP – right discs of drive wheelset no. 1,
Z1 NL – left discs of drive wheelset no. 1,
Z3 TP – right discs of rolling wheelset no. 3,
Z3 TL – left discs of rolling wheelset no. 3,
$Z_{1\text{-}6}$ – the sum of brake disc wear measured from the first to the first to the sixth P2 inspection in [mm],
T_1 – first rolling of the brake discs in [mm].

It was decided that in each period, during the P2 inspection related only to the geometric measurements of wheelsets, an additional activity was added to the replacement of wheelsets or bogies. Hence, periodic inspections from the first to the twelfth, in the middle of the period, i.e. in the planned date P2 - 12.08.2013, were extended to the aforementioned replacement of wheelsets. Similarly, in the period from 13 to 25 of the P2 inspection, in the middle of this period, i.e. on 28.07.2015, wheelsets or bogies were also replaced. In the last period, after the second rolling of brake discs between the 26th and 33rd periodic inspection on 11.02.2017, the last migration of bogies was also carried out.

4. RESULTS OF THE ANALYSIS

Figure 9 shows the characteristics of the change in the width of the brake discs from actual measurements (without the implementation of the wheelset management concept) on the analyzed EN76 vehicle. The graph, according to the data contained in Table 1, includes wear from 6 periods taking into account the collected brake disc wear data and brake disc rollover values in two periods.

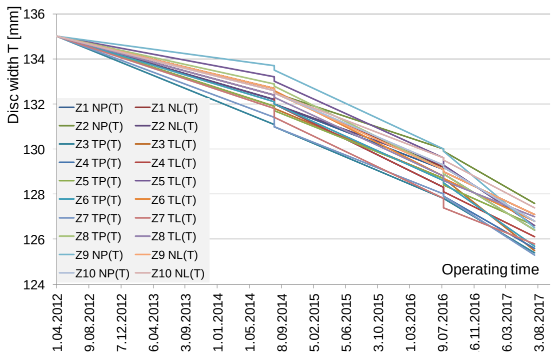

Fig. 9. Time-dependent width of brake discs for the classic approach to maintenance of wheelsets according to DSU based on the summed values of disc and shunt wear

Figures 10-12 show the models of disc width characteristics as a function of time after applying the EN76 vehicle bogie management concept, taking into account the bogie change periods according to Table 1.

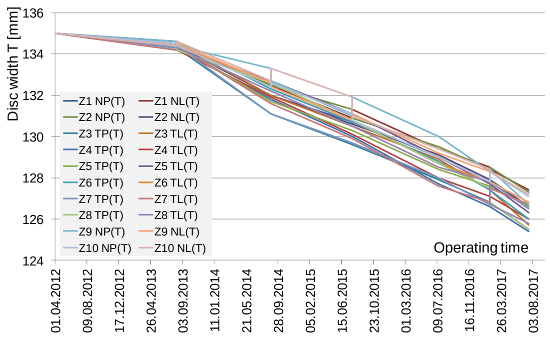

Fig. 10. Dependence of the width of the brake discs on the time for the castor swapping concept in the bogie

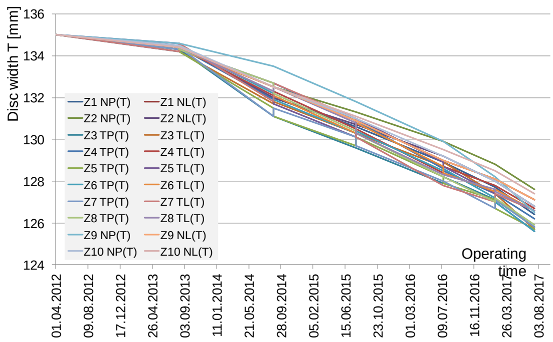

Fig. 11. Time-dependence of brake disc widths for bogie swapping concept without turning

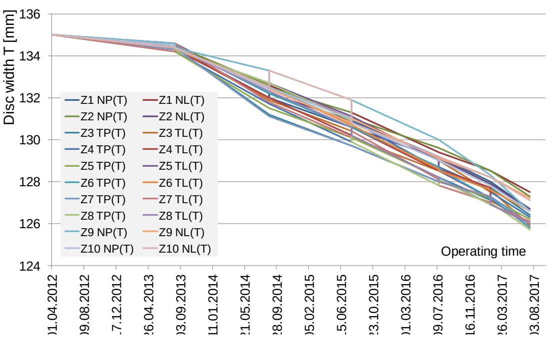

Fig. 12. Time-dependence of brake disc widths for the reversing bogie concept

Analyzing the graphs presented in Figures 10-12 after applying the 3 concepts in relation to Figure 9 without wheel set management, a slight reduction in the dispersion of brake disc width values was observed at the last P2 inspection. The dispersion of brake disc width values understood as the standard deviation for the best concept related to bogie migration in the entire vehicle was 0.52 mm with the classic approach without bogie management being 0.67 mm.

Figure 13 and Table 2 present the extreme values for brake disc widths (max and min values) that the analyzed traction unit would have obtained during the last periodic inspection after applying the 3 proposed bogie management concepts with 5 bogie replacement time periods..

Table 2. Brake disc width values obtained during the last periodic inspection P2 after the application of the analyzed bogie management concepts in the EN76 electric multiple unit in relation to the DSU compliant approach

	No trolley management	Trolley rotation	Swapping bogies without rotation	Swapping trolleys with swivel
Dimension max	127.6	127.4	127.6	127.5
Min dimension	125.3	125.4	125.6	125.7
Average	126.42	126.42	126.42	126.42
Standard deviation	0.668	0.600	0.600	0.525

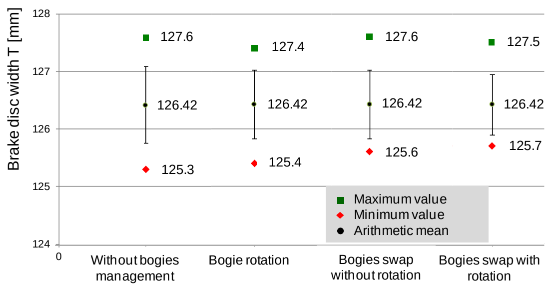

Fig. 13. Brake disc width values (maximum and minimum) obtained at the last P2 periodic inspection after the use of bogie migration in the EN76 vehicle in relation to the actual dimensions without management

Analyzing Figure 13, it was found that with 5 time periods allocated for the replacement of bogies, it is possible to increase (raise) the value of the minimum width of one of the discs for all considered concepts in relation to the classic approach to wheelset operation in accordance with the vehicle's DSU. For the bogie swapping concept, a minimum value of 125.7 mm was achieved at 125.3 mm without the use of bogie migration.

Table 3 shows the values of the minimum dimension increase in the brake disc width and the percentage of material savings per disc thickness after using the 3 bogie management concepts.

Table 3. Material savings over the width of the brake disc with the highest wear for the concepts analysed with regard to the approach without trolley migration

	Trolley rotation	Swapping bogies without rotation	Swapping trolleys with swivel
Recovery in [mm]	0.1	0.3	0.4
Recovery in [%]	1.0	3.0	4.0

In the qualitative (percentage) assessment, the savings associated with the recovery of the material over the width of the smallest disc size are between 1 and 4 %, depending on the concept used. Migration of the bogies with rotation ensures the greatest material recovery on the width of the brake discs and thus on their thickness (0.4 mm per 10 mm for a whole period of 5 years). The smallest increase was obtained for the concept of replacing wheelsets in the bogie, the increase in material was only 0.1 mm.

Table 4 shows the increments in the time converted into days of use and wheelset mileage in kilometres with the lowest dimension T.

Table 4. Increase in Vehicle Time and Mileage for the Analyzed Concepts for reducing brake disc wear (increasing the T dimension) in Relation to the Approach Without Bogie Migration

Conception	Minimum Dimension	Increase in days	Mileage increment
BASE	125.3 mm	0	0
Trolley rotation	125.4 mm	18	5874 km
Swapping bogies without rotation	125.6 mm	56	15642 km
Swapping trolleys with swivel	125.7 mm	61	25467 km

Analyzing the data contained in Table 4, it is found that the largest increase in the service life of a wheelset with brake discs and mileage is obtained using the method of migration of bogies with simultaneous rotation. In the case of brake discs, the service life was increased by more than 60 days, i.e. until the next P2 inspection (about 25500 km). Analyzing Table 4, it can be concluded that the wear of brake discs without implementing the bogie management concept was 0.0176 mm/1000 km, whereas implementing the bogie migration concept with rotation, the wear of brake discs will be 0.0168 mm/1000 km.

5. CONCEPT EVALUATION USING THE MUSES METHOD

The usefulness of the proposed concepts for the management of wheelsets or bogies in an electric multiple unit was carried out using the following evaluation criteria, such as:

- reduction of brake disc wear (increase brake disc width at the last periodic inspection P2),
- the time of making a rolling and driven bogie from a rail vehicle,
- the time of transport of the rolling and driven forklift to another place on the vehicle,

- the time of rotation of the rolling and drive bogie by 180°,
- the time of installation of the rolling and drive bogie on the vehicle,
- the tools required to disassemble and reassemble the wheelset or bogies,
- required lifting or lifting equipment,
- the number of people necessary to carry out a given concept,
- labor costs to implement a given concept.

The evaluation criteria for the analyzed three bogie management concepts in EMUs that can be implemented in rolling stock repair plants to extend the service life of wheelsets in terms of brake disc widths are presented in Table 5 together with the proposed evaluation.

Table 5. Evaluation criteria and evaluation for individual bogie management concepts in an electric multiple unit

	Swapping bogies without turning	Swapping trolleys with swivel	Trolley rotation
Increase in the min. dimension [%]	3.0	4.0	1.0
Lead time [min]	405	530	820
Equipment	2	3	3
Number of people	4	6	5
Cost [PLN]	758.70	1489.30	1920.17

Identifying the best forklift management concepts is related to solving decision-making problems based on selected evaluation criteria. For this purpose, it has been proposed to use a special method of multi-criteria programming, taking into account the multitude of objective functions [9]. The ordering (aggregation) of the decision criteria was carried out using the Zero Unitarization Method (MUZ) [17]. Three different variants were assumed in the understanding of the analyzed concepts. The variants were characterized by five characteristics (variables). The characteristic values of the wheelset or bogie management variants, taking into account the minimum and maximum values for the respective characteristic, are shown in Table 6 simultaneously for bogie management in terms of vehicle mileage extension for brake disc width T.

Table 6. Evaluation criteria and evaluation for individual bogie management concepts in an electric multiple unit

Variants	Features (variables)				
	X1	X2	X3	X4	X5
W1	3.0	405	2	4	758.70
W2	4.0	530	3	6	1489.30
W3	1.0	820	3	5	1920.17
Max xij	4.0	820	3	6	1920.17
Min xij	1.0	405	2	4	758.70

To solve the decision problem, it was necessary to recognize the variables for the analyzed concepts. The stimulant indicates the recommended higher values for a given variant, while the destimulant indicates the lower recommended values for the diagnostic variant. The stimulant is only one feature – X1, because it was described by the increase in the width of the brake discs in percentage compared to the classic approach without bogie management. Other features are destimulants and are related to the time of concept implementation, the number of technical devices, the number of employees and the costs of implementing a given concept. These qualities require the lowest values.

The norming of the variable (trait) was calculated on the basis of the relationship (2) and (3) [30]. For stimulants:

$$z_{ij,S} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{2}$$

For the destimulant:

$$z_{ij,D} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{3}$$

where: z_{ij} – i-th value of the normalized j-th variable,
x_{ij} – the value of a given feature (variable).

The last stage of the MUZ method was to calculate the value of the aggregate variable, which characterizes the analyzed concepts (variants) in terms of criteria, i.e. features. The calculation of the value of the aggregate variable for each variant and variable was made using the relation (4) [30]:

$$Q_i = \sum_j z_{ij} \tag{4}$$

where: Q_i – value of the aggregate variable assigned to the i-th variant.

Table 7 presents the results of standardization for the considered variants, while Table 8 presents the ranking and selection of the best variants, i.e. concepts for forklift management.

Table 7. Summary of standardization results for the considered bogie management variants in order to increase the minimum dimension of the brake disc width T compared to the approach without using the concept

Variants	Normalized variables					$Q_{i,T}$
	Z1	Z2	Z3	Z4	Z5	
W1	0.667	1	1	1	1	4.667
W2	1.000	0.699	0	0	0.371	2.070
W3	0	0	0	0.5	0	0.500

Table 8. Ranking and selection of the best concepts (variants) for management in the field of T

Concept	Variant	$Q_{i,T}$	Assessment
Swapping carriages without rotation	W1	4.667	MAX
Swapping carriages with rotation	W2	2.070	
Rotation of carriage	W3	0.500	

After conducting a multi-criteria analysis using the MUZ method, it was found that for the purposes of increasing the minimum dimension of both the width of the brake discs, taking into account all the criteria related to time, technical equipment, number of employees and the cost of implementing the concept, the best variant is the method of exchanging the bogies without rotating them. In this variant, the highest value of the aggregate variable was found. The second place is taken by the concept of exchanging the bogies with their rotation. It should be emphasized that the differences in the values of the aggregate variable Qi between variants W1 and W2 are significant (more than twice the value of Qi for variant W2 compared to W1). Based on the analyses and calculations, it is observed that variant W3 has the lowest practical usefulness.

6. CONCLUSIONS

The analyses of the implementation of 3 bogie management concepts allowed for the increase (raise) of the minimum width dimension value obtained by one of the twenty wheel sets before the P4 revision repair.

The largest increase in the vehicle's operating time and mileage is achieved on concepts arranged in the following order: bogie exchange with rotation, bogie exchange without rotation and the concept of changing wheel sets in the bogie, which also with the design possibilities of the bogie is identical with bogie rotation.

The increase in the minimum dimension for the width of brake discs, regardless of the implemented wheel set management concept, depends on the number of periods designated for bogie exchange. The greater the number of exchange periods, the greater the increase in the minimum dimension for the brake disc width T (from 0.4 to 1.0 mm).

The multi-criteria analysis conducted using the zero unitarization method MUZ showed that for all the considered concepts (variants) assessed on the basis of variables (features), it is best to use the bogie exchange method without rotation. The second place is taken by the method of changing the trolleys with rotation. In both cases, the highest values of aggregate variables of the analyzed variants were found despite the large differences between the methods. However, from the point of view of workload understood as the time of carrying out a given concept, employee involvement or costs, these methods were the fastest and cheapest.

The authors' future plans include testing the fourth concept of migrating wheel sets under the vehicle without dismantling the bogies and rolling them to other places under the vehicle.

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REFERENCES

1. Ambroszko W, Dudziński W, Walczak S. Finite Element Method analysis application in identifying the causes of brake disc failure. Combustion Engines 2024;197(2):71-82.https://doi.org/10.19206/CE-176212
2. Boguś P, Bocian S. Shape deformation analizys of rail car brakes with image processing techniques, Book of Abstracts of European Mechanics Society EUROMECH 406 Colloquium – Image Processing Methods in Applied Mechanics 1999; 6-8: 47-49. https://iopscience.iop.org/article/10.1088/1757-899X/148/1/012038/pdf
3. Brake monitor BWI 03 for disc brake axles. https://www.bpw.de/uploads/tx_szdownloadcenter/NEWSAllg03-10e.pdf
4. Chrzan M, Ciszewski T, Nowakowski W. Selected aspects of the diagnostic process in rail transport. Rail Vehicles/Pojazdy Szynowe 2023; 3-4: 3-12. https://doi.org/10.53502/RAIL-175048
5. Drożyner P, Brodecki A, Szymczak T. Stand testing of springs for drum break systems. Diagnostyka 2023; 24(4): 2023414. https://doi.org/10.29354/diag/177242
6. Gajek A. Diagnostics monitor of the braking efficiency in the on board diagnostics system for the motor vehicles. IOP Conference Series: Materials Science and Engineering 2016; 148: 012038. https://iopscience.iop.org/article/10.1088/1757-899X/148/1/012038/pdf
7. Gajek A. Proposed method of checking the braking efficiency coefficient for motor vehicles with hydraulic braking systems. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2016; 73(3): 19-30. http://dx.doi.org/10.14669/AM.VOL73.ART2
8. Ganeshan R, Darbha S. A diagnostic machine learning algorithm for air brakes in commercial vehicles. IFAC PapersOnLine 2024; 58-10: 75–80. https://doi.org/10.1016/j.ifacol.2024.07.321
9. Helak M, Kadziński A. Changes in maintenance of railway vehicles as the sources of threats in the railway system. Scientific Journal of the Military University of Land Forces 2020; 1(195): 112-120. https://doi.org/10.5604/01.3001.0014.0267
10. Hou Z, Lee CKM, Lv Y, Keung KL. Fault detection and diagnosis of air brake system: A systematic review. Journal of Manufacturing Systems 2023; 71: 34-58. https://doi.org/10.1016/j.jmsy.2023.08.005
11. Jakubowski A, Kaluba M, Goliwąs D. Mechatronic controller of brake pipe pressure. Rail Vehicles/Pojazdy Szynowe 2023; 1-2: 8-13. https://doi.org/10.53502/RAIL-168490
12. Jegadeeshwaran R, Sugumaran V. Fault diagnosis of automobile hydraulic brake system using statistical features and support vector machines. Mechanical Systems and Signal Processing 2015; 52-53: 436-446. https://doi.org/10.1016/j.ymssp.2014.08.007
13. Jensen KM, Santos IF, Corstens HJP. Estimation of brake pad wear and remaining useful life from fused sensor system, statistical data processing, and passenger car longitudinal dynamics. Wear 2024; 538-539: 205220.

14. Jensen KM, Santos IF, Corstens HJP. Prediction of brake pad wear and remaining useful life considering varying vehicle mass and an experimental holistic approach. Wear 2024; 552-553: 205433. https://doi.org/10.1016/j.wear.2024.205433
15. Kanis J, Zitrický V, Hebelka V, Lukáč P, Kubín M. Innovative diagnostics of the railway track superstructure. Transportation Research Procedia 2021; 53: 138–145. https://doi.org/10.1016/j.trpro.2021.02.017
16. Komorski P, Kominowski J, Motyl M. A proposal for a mobile system of vehicle and rail track diagnostics. Transport Problems 2022; 17(2): 45-56. https://doi.org/10.20858/tp.2022.17.2.04
17. Kukuła K, Bogocz D. Zero Unitarization method and its application in ranking research in agriculture. Economic and Regional Studies 2014; 7(3): 5-13.
18. Matej JL, Orliński P. Reducing wheel wear of a motorised metro car on a curved track with a small curve radius. Rail Vehicles/Pojazdy Szynowe 2023; 3-4: 25-32. https://doi.org/10.53502/RAIL-175921
19. Matusiak K, Goliwąs D, Kaluba M. Adsorption dryer for use in railways. Rail Vehicles/Pojazdy Szynowe 2022; 1-2: 77-85. https://doi.org/10.53502/RAIL-152486
20. Marina E, Daimonc E, Boschettoa F, Rondinellaa A, Inadad K, Zhua W. Diagnostic spectroscopic tools for worn brake pad materials: A case study. Wear 2019; 432-433: 202969. https://doi.org/10.1016/j.wear.2019.202969
21. Paś J, Białek K, Wetoszka P. Effects of independent magnetic fields in the very low frequency range elf generated by selected elements of an electric traction unit on the ambient environment and electronic systems. Journal of Automation, Electronics and Electrical Engineering 2022; 4(1): 29-35. https://doi.org/10.24136/jaeee.2022.004
22. Roczek K, Krol A. Clutch-brake unit - principle of operation and basic diagnostic methods. Diagnostyka 2018;19(1):33-39. https://doi.org/10.29354/diag/80975
23. Sawczuk W, Rilo Cañás AM, Kołodziejski S. Testing the wear of wheelsets of EN97 series vehicles in terms of geometrical parameters of the wheel profile in two-year operation. Rail Vehicles/Pojazdy Szynowe 2023; 1-2: 38-45. https://doi.org/10.53502/RAIL-171570
24. Sawczuk W, Ulbrich D, Kowalczyk J, Merkisz-Guranowska A. Evaluation of Wear of Disc Brake Friction Linings and the Variability of the Friction Coefficient on the Basis of Vibroacoustic Signals. Sensors 2021; 21(17): 5927-1-5927-21. https://doi.org/10.3390/s21175927
25. Sawczuk W, Merkisz-Guranowska A, Rilo Cañás AM. Assessment of disc brake vibration in rail vehicle operation on the basis of brake stand. Maintenance and Reliability 2021; 23(1): 221-230. https://doi.org/10.17531/ein.2021.2.2
26. Segal L. Diagnostic method for vehicle brakes. NDT&E International 1999; 32: 369–373.
27. Setién J, González JJ, Polanco JA. Cracking diagnostics of brake pedals during press forming operations. Engineering Failure Analysis 2000; 7: 69-74.
28. Świderski A, Borucka A, Jacyna-Gołda I, Szczepański E. Wear of brake system components in various operating conditions of vehicle in the transport company. Maintenance and Reliability 2019; 21(1): 1-9. https://doi.org/10.17531/ein.2019.1.1
29. You SH, Hahn JO, Cho YM, Kang S, Lee KII. A fault diagnostics algorithm for differential brake control system. Elsevier IFAC Publications. Tokyo, Japan 2003: 275-280.
30. Zadrąg R, Kniaziewicz T. Utilization of the zero unitarization method for the building of a ranking for diagnostic marine engine parameters. Combustion Engines 2017; 171(4): 44-50. https://doi.org/10.19206/ce-2017-408
31. Zhang M, Li X, Xiang Z, Mo J, Xu S. Diagnosis of brake friction faults in high-speed trains based on 1DCNN and GraphSAGE under data imbalance. Measurement 2023; 207: 112378. https://doi.org/10.1016/j.measurement.2022.112378

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