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# Maintenance of disc-brake wheelsets

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*This article discusses the maintenance of disc brake wheelsets. The wheel set of a rail vehicle, along with the disc brake, is the basic unit of a rail vehicle, susceptible to abrasive wear. In the case of railway wheels, wear results from contact with the rail, while for brake discs, wear occurs through friction with the friction lining. The wear process of both wheels and brake discs is uneven, which for the operator requires shutting down the vehicle, once when the discs reach their maximum wear limit, and again when the wheels reach their wear limit. This article presents the results of wheel and brake disc wear tests and their analysis over a 5-year period on a selected ELF I electric multiple unit. Based on the test results, it was concluded that for a multi-unit vehicle such as a multiple unit, it is necessary to monitor the wear rate of wheels and brake discs during the P2 periodic inspections and to implement organizational and technical measures to achieve longer service life for one of the wheelset components. Such actions will allow to obtain similar values of the wear limit of the wheel and disc at the P4 inspection, i.e. during the revision repair.*



## 1. Introduction

In modern railway rolling stock, the disc brake is the primary component responsible for stopping a train running at speeds above 120 km/h in the shortest possible braking distance. There is also a main service brake that provides PN braking. Freight wagons, due to their lower speeds, use a block brake with composite brake blocks. In this case, freight wagons are designated with the symbol S or SS. For wagons for S traffic, this refers to a speed of up to 100 km/h with an axle load of 225 kN, and for wagons for SS rail traffic, this refers to a speed of up to 120 km/h with a wheelset axle load of 200 kN [9]. These wagons are already equipped with a disc brake on the wheelset axle. The disc brake, in relation to the block brake, enables the rapid absorption and dissipation of the motion energy, which is particularly important for safety and, in passenger trains, also for the comfort of travel [12].

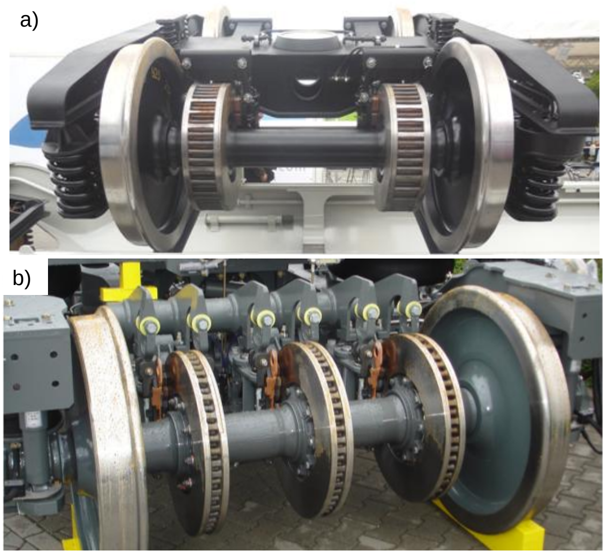


Fig. 1. View of the wheelset of: a) a freight wagon for SS traffic, b) a passenger wagon [W. Sawczuk]

Traction units are currently built for speeds up to 160 km/h as multi-unit trains without the possibility of splitting them. In traction units, the disc brake is at-

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tached to the railway wheel on both sides [13]. Figure 1 shows a view of rolling wheelsets with disc brakes. Figure 2 shows a view of wheelsets from a traction unit, on the axle of which, in addition to the brake discs, the gear wheel of the traction motor is mounted.

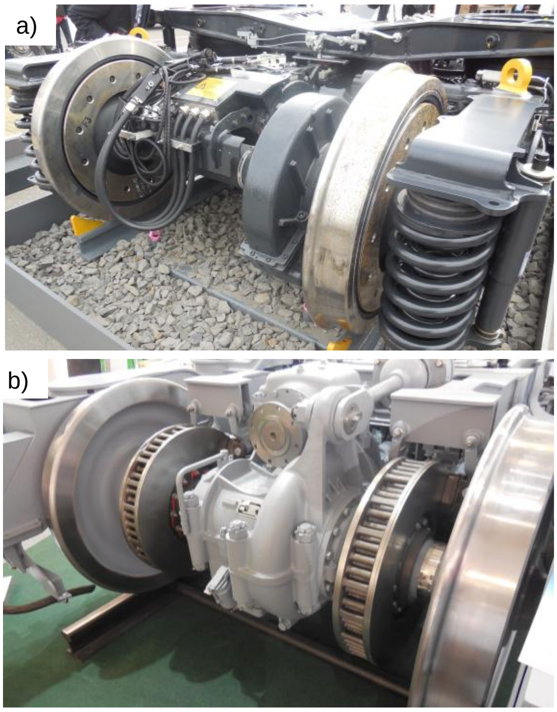


Fig. 2. View of the driven wheelset: a) with discs on the wheel, b) with discs on the axle [W. Sawczuk]

The mounting of brake discs to the wheel is due to the limited space under the vehicle body on the bogie due to the presence of traction motors and a gearbox. Older traction unit designs featured classic wagon discs mounted to the axles of the wheelset. However, the development of both diesel and electric multiple units in achieving increasingly larger lowered floor areas resulted in the brake discs being moved to the wheel [5]. Due to the gearing found on the refined driving bogies, achieving a 100% lowered floor is impossible only in these units (with cabins). A similar trend occurred in tram construction, where due to the longitudinal and external placement of the motors, a 100% lowered floor is achieved. An example is the Siemens Combino tram [8]. Currently, the friction brake is electronically controlled in EP mode, but due to the presence of driving wheelsets, braking is possible with traction motors generating resistance during generator operation [21, 25]. This type of braking using traction motors is called electrodynamic braking (ED) and reduces the wear of the disc brake discs and friction linings on the drive wheelsets [2, 22]. The aim of this article is to assess the wear of the wheels and brake discs on the drive rolling wheelsets of a selected ELF I electric multiple unit, which was operated for a period of 5 years from the start of scheduled operation until the first P4 inspection.

## 2. Research object

The test object were 4 electric multiple units PESA EN76 ELF I, as shown in Fig. 3. The vehicles were manufactured as four-unit units, but the number of units depends on the order of a given owner or railway carrier [14].

Fig. 3. View of the PESA ELF I vehicle [A.M. Rilo Cañás]

PESA ELF electric multiple units are designed for domestic passenger transport. The vehicles operate in most Polish provinces, covering routes within one or two provinces [7, 24]. PESA ELF vehicles are built with end units under which bogies with electric motors are located, while the remaining units (wagons) are equipped with trailer bogies. The power wagons under cabins A and B are equipped with classic two-axle bogies, while the remaining units are equipped with Jakobs trailer bogies at the ends, connecting the end of one wagon to the beginning of the next [1, 3].

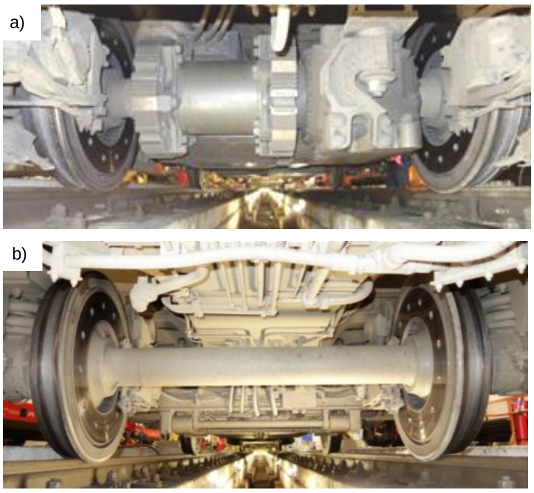


Fig. 4. View of the wheelsets of the PESA ELF I vehicle: a) drive with visible engine, gearbox and brake discs, b) rolling with brake discs only [A.M. Rilo Cañás]

Figure 4 shows a view of the wheelsets with brake discs mounted on the wheels. Due to the lowered floor over a large section [15, 33], the vehicle is equipped with a disc brake with discs mounted on the wheels to avoid unnecessary construction of the central section of the bogie with a lever mechanism. In the case of the drive bogies, the discs mounted on the wheels were dictated by the size of the traction motors and gears. The basic technical parameters of the PESA ELF I are presented in Table 1.

Table 1. Basic technical data of the EN76 vehicle [6]

| No. | Name | Value | Unit |
|---|---|---|---|
| 1 | Track gauge | 1435 | mm |
| 2 | Total unit length with buffers | 75 250 | mm |
| 3 | Widest unit width | 2883 | mm |
| 4 | Largest unit height from railhead | 4280 | mm |
| 5 | Bolt spacing | 4×16 300 | mm |
| 6 | Traction unit power | 4×500 | kW |
| 7 | Main circuit voltage | 3 kV DC | kV |
| 8 | Maximum operating speed | 160 | km/h |
| 9 | Acceleration to 40 km/h | 1.0 | $m/s^2$ |
| 10 | Braking deceleration | 1.2 | $m/s^2$ |
| 11 | Service weight | 134.5 | t |
| 12 | Wheel rolling diameter (new/worn) | 850/780 | mm/mm |

The primary advantage of the PESA ELF I vehicles is their modular design, depending on the order. The vehicle can be delivered in two to six sections, depending on the number of passengers being transported. Another advantage is its design speed of 160 km/h, which, since 2010, when the vehicle was manufactured, has been considered a high speed in urban areas.

## 3. Research methodology

Four PESA ELF I type vehicles were selected to assess the wear of wheel sets with brake discs mounted to the wheels [18]. The research was a passive experiment [10, 11] and was conducted for a period of approximately 5 years from the first periodic P2 inspection to the first P4 level inspection, i.e. revision repair. During the tests, the wheel diameter D and the brake disc thickness T were recorded (Fig. 5).

The remaining wheel profile parameters were not analyzed or evaluated because the wheel diameter D was the most frequently exceeded parameter observed during the P2 inspection compared to the other parameters. The same conclusions were reached by the authors of [19] during wear tests on the wheelsets of the EN97 vehicle (Fig. 6).

The analyzed PESA ELF I vehicles operated in one voivodship on three different routes, as shown in Table 2. The rail carrier deliberately varied the vehicle routes to achieve similar wheel wear values. If the vehicle operated on only one route, the wheels would wear out faster than other vehicles due to the different number of curves.

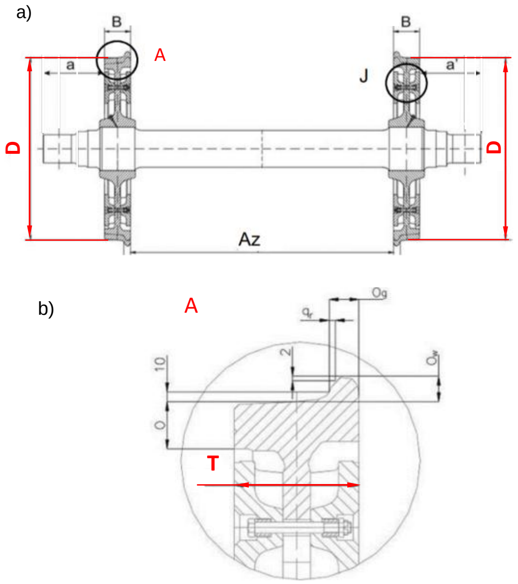


Fig. 5. Cross-section of: a) rolling wheel set with dimension D, b) detail A of the wheel rim with brake disc and dimension T [4]

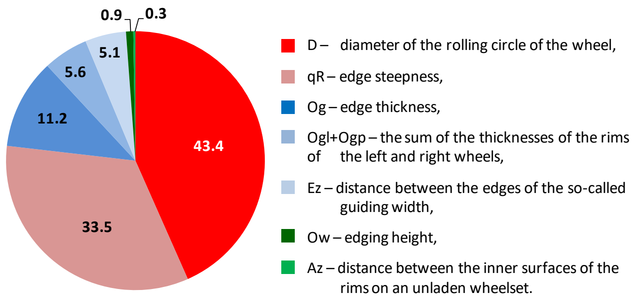


Fig. 6. Summary of percentage exceedances of a given wheel set parameter detected during P2 for 14 EN97 vehicles over a two-year period [19]

Table 2. Driving routes of the tested PESA ELF I vehicles

| Line number | First, intermediate and last station | Length of the route |
|---|---|---|
| 3 | Poznań Główny–Zbąszynek | 81 km |
| 353 | Poznań Główny–Gniezno–Mogilno | 80 km |
| 3 | Poznań Główny–Konin–Kłodowa–Kutno | 179 km |

Additionally, to even out wheel flange wear, the vehicles were rotated with their cabs in the direction of travel after P2 inspections. Wheel wear tests for EN76 series vehicle wheelsets were conducted based on analysis of the geometric parameters of the wheelsets recorded during the P2 inspection, in accordance with the inspection and repair cycle included in the maintenance system documentation (Table 3).

Table 3. EN76 [4] Electric multiple unit inspection and repair cycles

| Maintenance level | Maximum mileage in km | Maximum time |
|---|---|---|
| P1 | – | every 9 day ±1 |
| P2 | – | every 2 months ±5 day |
| P3 | every 200 000 km ±5% | every 12 months ±10 day |
| P4 | every 1000 000 km | 5 years |
| P5 | every 3000 000 km | 15 years |

Table 4 shows the mileage and operating time for the tested vehicles from the moment they started regular transport after being handed over from the manufacturer.

Table 4. Data on the operating time of the tested EN76 vehicles

| Vehicle number | Operating time | Mileage |
|---|---|---|
| 026 | 5 years, 7 months, and 22 days | 614 916 km |
| 028 | 5 years, 5 months, and 12 days | 627 807 km |
| 030 | 5 years, 3 months, and 9 days | 612 364 km |
| 031 | 5 years, 12 days | 591 988 km |

The average mileage of the EN76 electric multiple unit vehicles analyzed for wheel wear prior to the P4 inspection was 611,768.75 km. Referring to Table 4, the EN76 series vehicles did not reach 1 million kilometers in a 5-year period. The wheelsets had a large dimensional margin. The vehicle owner decided to change the provision in the DSU to extend the P4 repair period to 6 years.

## 4. Research results

During the tests, only the wheel diameter D and the brake disc thickness T were recorded. Table 5 presents an example view of the developed measurement card for two wheel set parameters from a single P2 inspection for the first (example) vehicle. After entering the measurement card into an Excel spreadsheet, the maximum and minimum dimensions for D and T were searched and marked. The wheel diameter and brake disc thickness were monitored until the inspection. First, the characteristics of the maximum and minimum dimensions of the wheel diameter and brake disc thickness were determined.

Table 5. Sample measurement sheet of the D and T parameters from the P2 inspection for the EN76 vehicle number 026

| Wheel set number | Wheel diameter D in [mm] | | Disc thickness T in [mm] | |
|---|---|---|---|---|
| | L | P | L | P |
| 1 | 839.1 | 838.9 | 130.9 | 130.9 |
| 2 | 839.5 | 839.6 | 130.9 | 131.1 |
| 3 | 847.1 | 846.6 | 130.4 | 129.7 |
| 4 | 847.5 | 847.1 | 130.0 | 130.1 |
| 5 | 847.9 | **847.8** | 130.9 | 130.2 |
| 6 | 846.6 | 846.2 | 130.4 | 130.3 |
| 7 | 847.3 | 847.5 | 129.3 | 129.5 |
| 8 | **848.0** | 847.7 | 130.4 | 130.7 |
| 9 | 837.3 | 837.6 | 130.4 | **131.3** |
| 10 | 837.1 | 837.2 | **131.0** | 130.9 |

L – Left wheel (disc), P – Right wheel (disc)
Bold, e.g., 848.0, indicates the maximum dimension for the disc and wheel.
Underlined, e.g., 837.1, indicates the minimum dimension.

Figure 7 shows the dependence of the maximum and minimum dimensions of the right wheels and brake discs of all 10 wheel sets as a function of operating time. Similar results for the analyzed vehicle were obtained for the left wheels and discs.

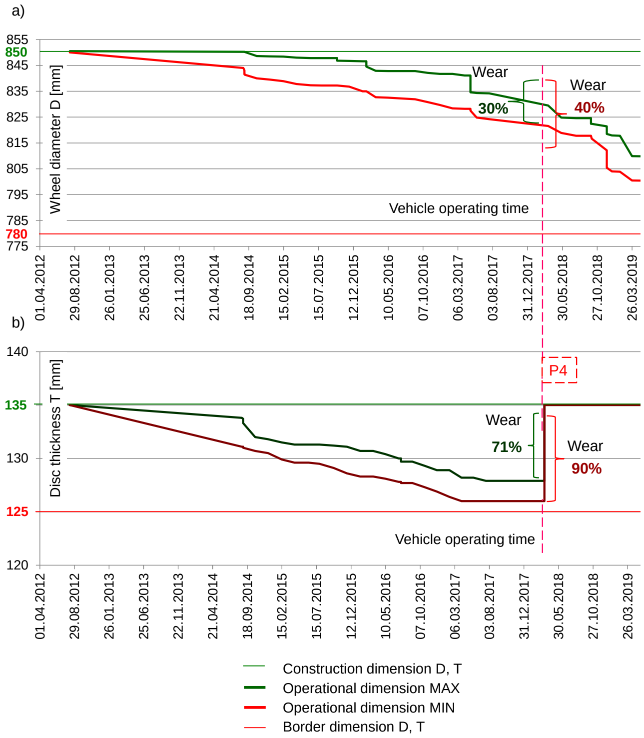


Fig. 7. Dependence of: a) wheel diameter in the rolling circle, b) brake disc thickness on the operating time, observed during P2 inspections up to P4 inspection for the right side

Analyzing Fig. 7, it was found that brake discs wear in the range of 70–90%. Some vehicles experienced 100% wear on a single wheel set over a 5-year period, unlike railway wheels. Railway wheels wear in the range of 30–40% after 5 years. This was the basis for extending the right inspection period by one year (6 years) to ensure that the wheels also reach a dimension close to full wear after replacing the discs with new ones. Unfortunately, replacing full discs with new ones requires pressing the wheel off the axle to install the new discs, and pressing the wheels back onto the axle carries the risk of the wheel scratching the axle and requiring the wheels to be replaced as well.

Then, based on the collected data from the measurements of wheel diameter and brake disc thickness during all periodic inspections of level P2 from the time of commencement of scheduled runs to the first inspection of level P4, the distributions of 10 wheelsets with right wheels with the maximum and minimum dimensions D and T were determined. The distributions of wheelsets were made as histograms of the number of cumulative wheel diameter D and brake disc thickness T. Then, a ranking of wheelsets was determined in which the maximum dimension of the wheel diameter indicating the lowest wear and the minimum dimension (the greatest wheel wear) were most frequently found during P2 inspections. The same applies to disc thicknesses within the range of maximum and minimum dimensions observed during P2.

Table 6. Numbers and frequencies for the maximum and minimum dimensions of the wheel diameter and the thickness of the vehicle discs 026

| No. | Left wheels | | | |
|---|---|---|---|---|
| | Magnitude li max for D | Frequency pi max for D | Magnitude li min for D | Frequency pi min for D |
| 1 | 0 | 0 | 6 | 0.200 |
| 2 | 0 | 0 | 4 | 0.133 |
| 3 | 2 | 0.061 | 0 | 0 |
| 4 | 5 | 0.152 | 0 | 0 |
| 5 | 16 | 0.485 | 0 | 0 |
| 6 | 1 | 0.030 | 0 | 0 |
| 7 | 2 | 0.061 | 0 | 0 |
| 8 | 7 | 0.212 | 0 | 0 |
| 9 | 0 | 0 | 5 | 0.167 |
| 10 | 0 | 0 | 15 | 0.500 |
| ∑ | 33 | 1 | 30 | 1 |
| No. | Left disc brakes | | | |
| | Magnitude li max for T | Frequency pi max for T | Magnitude li min for T | Frequency pi min for T |
| 1 | 5 | 0.192 | 0 | 0 |
| 2 | 17 | 0.654 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 7 | 0.233 |
| 6 | 0 | 0 | 12 | 0.400 |
| 7 | 0 | 0 | 11 | 0.367 |
| 8 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 |
| 10 | 4 | 0.154 | 0 | 0 |
| ∑ | 26 | 1 | 27 | 1 |

Table 6, based on the example of one vehicle 026, presents the results of the number of occurrences li of the given dimensions max D(T) and min D(T) and the relative frequencies pi. Figure 8 presents the histogram of the frequency of occurrence of the maximum and minimum dimensions of the wheel diameter and the thickness of the brake discs on all wheel sets. The minimum dimensions are marked in red and orange, and the maximum dimensions are marked in green.

Analyzing the results in Table 6 and the histographs in Fig. 8, it was found that in each case, the driving bogies had the highest wheel wear. On these bogies, the outermost wheelsets (the first and last bogies) had the highest wheel wear across the diameter. However, the rolling wheelsets had the lowest wheel wear because they had the largest diameters during inspections compared to the driving wheelsets. If a bar is missing in the relative frequency graph (Fig. 8), it means that the given wheelset never reached its maximum or minimum diameter during periodic inspections. In the case of brake discs, the phenomenon was the opposite of the wear of railway wheels. Driving wheelsets with outermost wheelsets had the discs with the least wear (green bars in Fig. 8b), while the rolling wheelsets had the highest wear (orange bars in Fig. 8b).

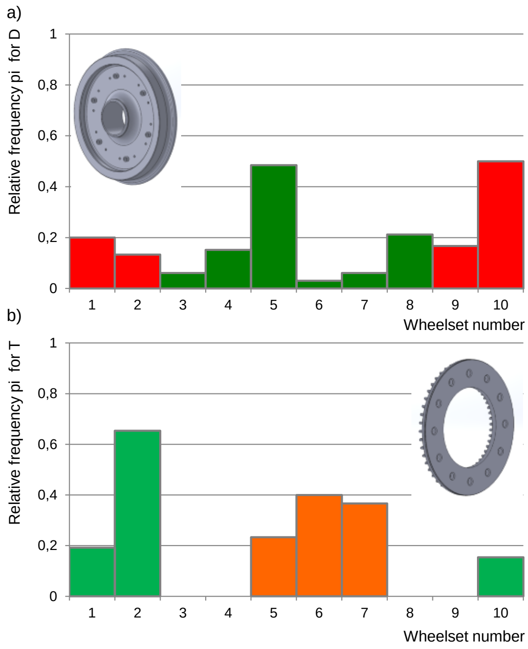


Fig. 8. Distribution of the relative frequency of occurrence of the maximum dimension (green and light green) and the minimum dimension (red and orange) for: a) wheel diameter D, b) disc thickness T of vehicle 026

Based on the data collected from the wheel diameter measurements, the total wear of the right wheels over a 5-year period was calculated for the PESA ELF 026 vehicle, as shown in Fig. 9. This figure also shows the value of all wheel re-turns over a 5-year period of operation.

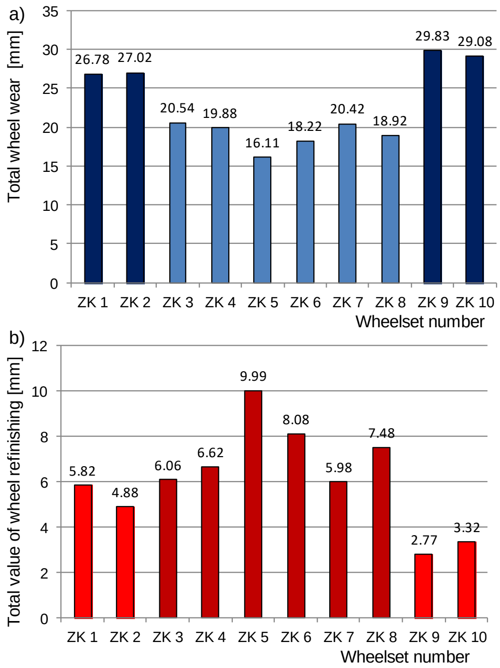


Fig. 9. Total value of: a) linear wear of wheels, b) wheel wear on individual wheel sets of the vehicle EN76 026

Analyzing the graphs presented in Fig. 9, it was found that the outermost wheelsets showed the greatest wear relative to the rolling sets. However, in the case of the values of wheel turning on the wheelset lathe, the rolling sets were the most frequently machined.

Figure 10 presents the total brake disc wear values and the sum of all brake disc refinishing values. Based on these graphs, it was found that the drive units showed lower brake disc wear values compared to the rolling units, which can be explained by the additional contribution of the electrodynamic brake on the vehicle's end bogies. On the drive units, the average refinishing value was 0.30 mm, while on the rolling units it was 0.42 mm.

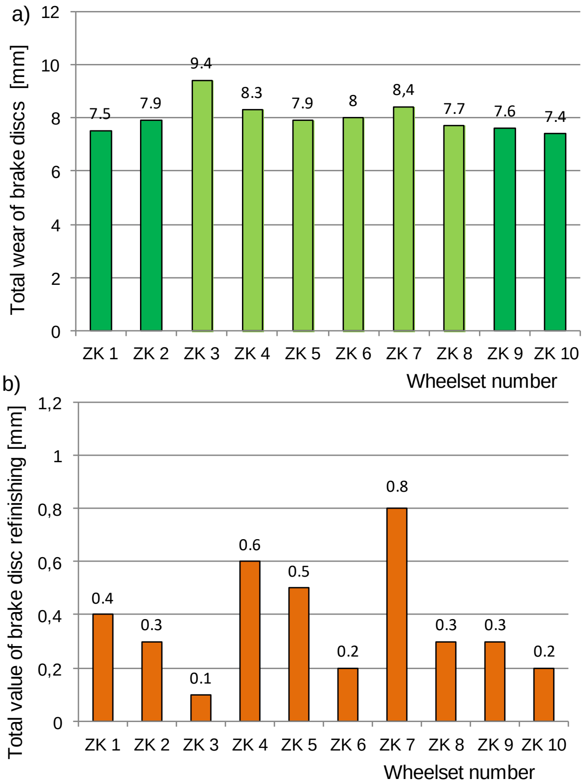


Fig. 10. Total value of: a) linear wear of brake discs, b) wear of brake discs on individual wheel sets of the vehicle EN76 026

Table 7 shows the average wear values of wheels and brake discs over a 5-year period.

Table 7. Average wear values of wheels and brake discs on the drive and rolling sets of the analyzed EN76 026 vehicle after 5 years of operation until the P4 inspection

| Wheel sets | | Average wheel wear value | Average disc wear value |
|---|---|---|---|
| Drive units | ZK1, ZK2, ZK9 and ZK10 | 32.4 mm | 7.9 mm |
| Rolling units | ZK3, ZK4, ZK5, ZK6, ZK7, ZK8 | 26.4 mm | 8.7 mm |
| Difference between drive and rolling units | | 6 mm | 0.8 mm |

Based on Fig. 9 and 10 and the average wear values for wheels and discs presented in Table 7, it was found that there is a difference between the rolling and driving sets in each case. In the case of railway wheels, the wear is lower on the rolling sets than on the driving sets. However, in the case of brake discs, the relationship is reversed.

Figure 11 shows examples of defects observed during the P2 inspection of the running surface of EN76 series vehicle wheelsets. Figure 12 shows a view of the brake discs.

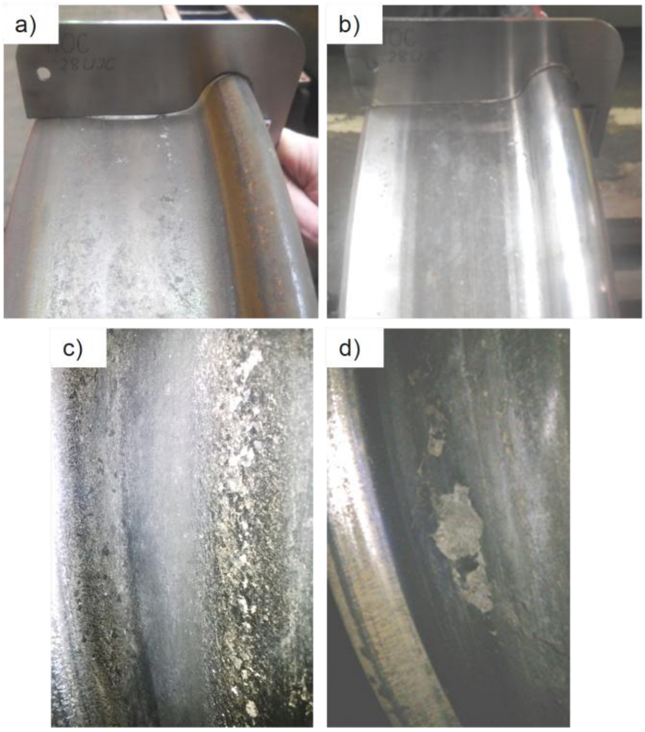


Fig. 11. View of the rolling surface of the vehicle wheels EN76 026: a) with visible wear in the contact area, b) view of the surface after rolling, c) flaking, d) chipping [A.M. Rilo Cañás]

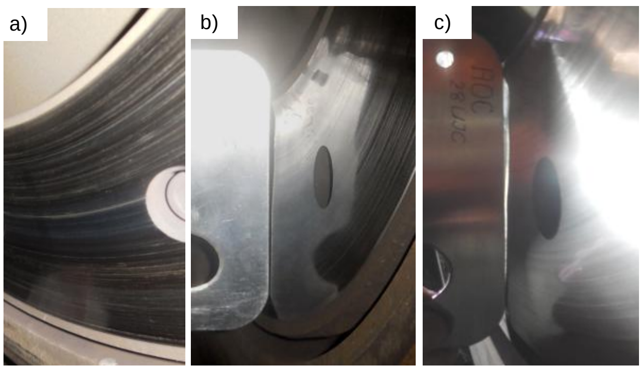


Fig. 12. View of the friction surface of EN76 026 vehicle brake discs: a) scratches on different diameters, b), c) view of linear wear around the inner radius [A.M. Rilo Cañás]

Figures 11c and 11d show a few minor defects in the wheel surface material, while Fig. 11a and 11b show examples of frictional wear resulting from wheel-rail contact. Abrasion of the wheel surface is observed across a portion of the wheel width after applying the UIC 28 wheel profile gauge. The presence of various surface defects led to the decision to turn the wheels on track-floor wheel set lathes. Analyzing the friction surface views of the brake discs (Fig. 12) of the analyzed EN76 series vehicles revealed only linear wear, predominantly on the inner radius of the disc, and scratches on various brake disc diameters. Visible scratches from the wear point are the result of various metallic particles present in the friction material and the ingress of sand or other contaminants from the track. Thermal cracks described in [26, 27], which dominate in passenger carriages with disc brakes, were not observed in any case.

## 5. Concepts for extending the service life of brake discs

The first way to theoretically and seemingly extend brake disc life was to change the method of measuring disc wear. In the first version of the DSU document, disc wear was measured using a caliper to measure disc thickness. This measurement is taken in several places from the inner to the outer radius to obtain the smallest dimension.

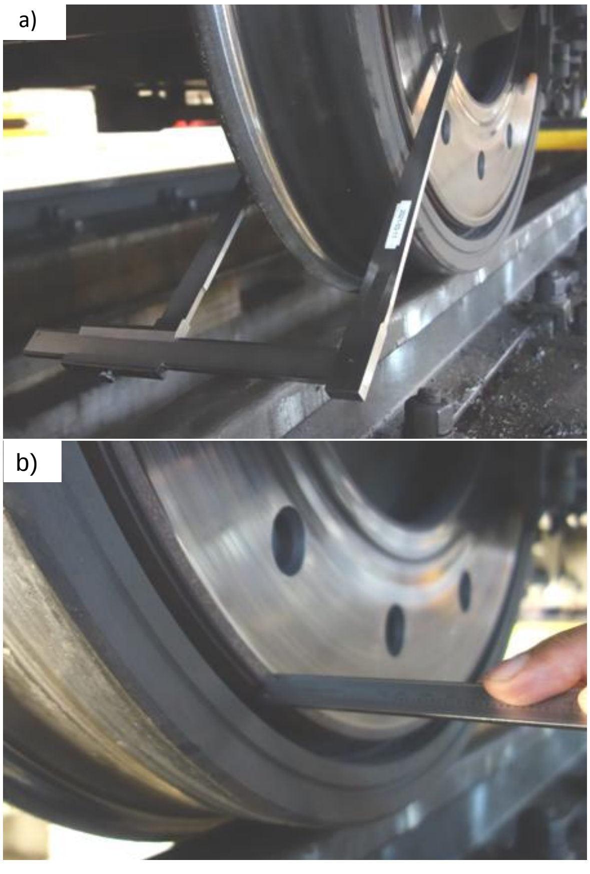


Fig. 13. Geometric measurement of brake discs. a) brake disc width (dimension T), b) brake disc control groove depth (dimension R) [W. Sawczuk]

In EN76 vehicles, the discs are bolted to both sides of the wheel, and the design thickness of new discs T is 135 mm, with wear up to 125 mm (5 mm for each disc). In the second version of the DSU document, the measurement of disc thickness T was changed to measuring the depth of the control groove located on the outer radius of the disc, while simultaneously measuring the grooves (recesses) on the brake disc. A new brake disc has a groove cut at a depth of 5 mm on its outer radius. The absence of a visible groove indicates complete and permissible brake disc wear and requires replacement with a new disc. It should be noted that the friction pads in contact with the brake disc are smaller than the difference in the disc radii, i.e., the outer and inner radii. The friction pad does not contact the disc at the control groove. In operation, the disc will wear linearly across the width of the pads, but there will be no wear on the inner and outer edges of the brake disc. Only a visual inspection of the disc surface, measuring the surface waviness from the inner to the outer radius, will prompt the disc to be turned over its entire surface. Depending on the turning depth, the control groove dimension will decrease. Figure 13 shows how to assess brake disc wear by measuring disc thickness and the control groove.

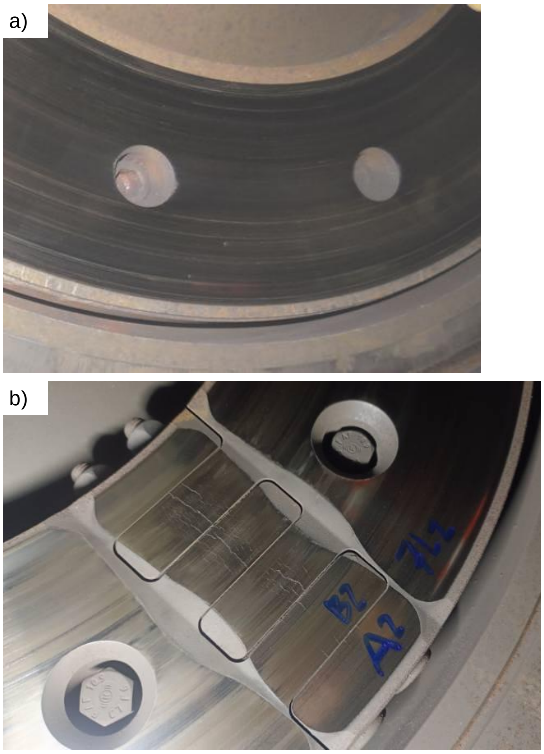


Fig. 14. View of the brake disc from the EN76 electric traction unit, a) full (older solution), b) divided (view at the point where the segments are joined) [A.M. Rilo Cañás]

Another way to extend the life of a wheelset when the brake disc wears faster than the wheels is to use segmented (split) discs instead of solid discs [20].

Both electric and diesel multiple units commonly use solid (monolithic) brake discs. When the wear limit and maximum wear limit are reached, they can be removed from the outer side of the wheelset (from the bearing housing side) without pressing the wheels off the axle. For discs mounted on the inside of the wheelset, removing the discs and installing new ones requires pressing the wheels off the axle. In each case, the wheelset must be removed from the bogie. Removing solid discs is not a problem for entities responsible for maintaining ECM railway vehicles; disc removal is performed by unscrewing them from the wheels and cutting them in two places. Unfortunately, installing new solid discs requires pressing the wheel off the axle to mount the discs on the inner side of the wheel, and dismantling the housing with the bearing without pressing the wheel off the axle to mount the discs on the outer side of the wheel. Figure 14 shows a comparison of a solid disc and a split disc for an electric traction unit.

The use of split discs in railway technology, due to their faster wear compared to the wheels, was already known much earlier. In 2000, a wheelset for a 1435- to 1520-mm gauge changeover system, designed by Dr. Ryszard Suwalski, was presented. In this wheelset, the designer deliberately used four-segment brake discs of his own design, mounted at the center of the wheelset axle between the wheel changeover and locking mechanisms, as shown in Fig. 15.

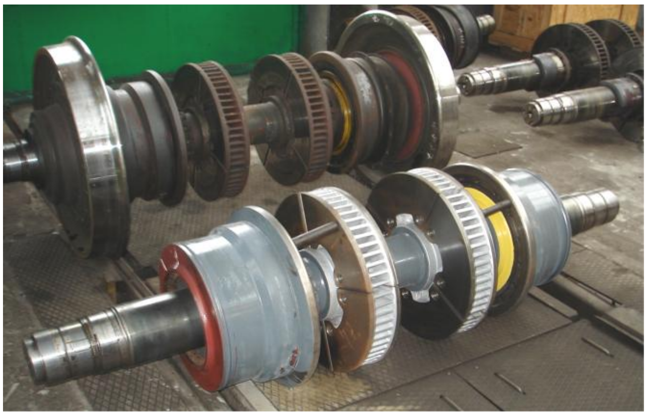

Fig. 15. View of the axle and the 1435/1520 mm SUW 2000 adjustable wheel set with split discs [W. Sawczuk]

A third way to extend the service life of a wheel set with brake discs is to migrate the wheelsets or bogies from the areas under the vehicle with the highest wear to the areas with the lowest brake disc wear. This issue was already discussed by one of the co-authors in [16]. This approach will extend the vehicle's service life and mileage on the set that has been characterized by the highest wear intensity from the beginning of operation. This will also accelerate wear on the set that has had the slowest brake disc wear from the beginning of operation. From a technical perspective, this is not a disadvantage of the bogie or wheel set management method, as during a revision repair after a period of 5 or 6 years (depending on the vehicle type), all wheelsets are replaced with new ones.

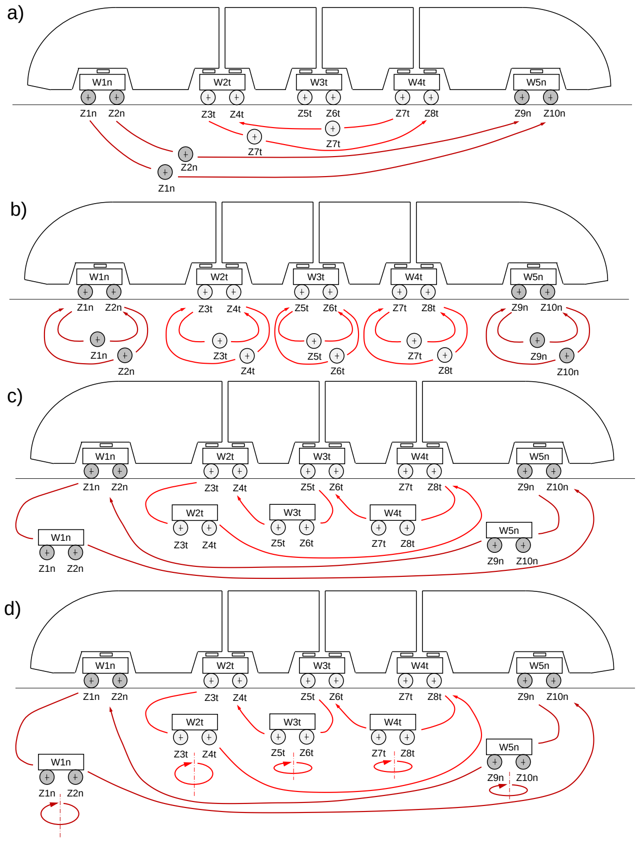


Fig. 16. Concepts of migration (swapping) of wheelsets or bogies: a) migration of wheelsets, b) rotation of the bogie, c) migration of bogies without rotation, d) migration of bogies with rotation

Based on the experience of the authors [16], as shown in Fig. 16, it is possible to implement the following concepts of replacing wheelsets or bogies:

- replacement (by moving) all wheel sets with discs under the vehicle
- rotation of bogies or swapping wheelsets within a single bogie
- swapping (migration) the bogies under the vehicle without turning them over
- swapping the carriages with simultaneous rotation.

Based on the data from the operation of the ELF I vehicle number 026 over a period of 5 years until the first P4 revision repair, it was checked how the width of the discs would change after implementing the concept of replacing the wheelsets or bogies. Knowing the brake disc width values at each P2 inspection and the disc re-rolling values, we examined how the width dimension T would change at the last P2 inspection before the revision. Figure 17 and Table 8 present the extreme values for brake disc width (maximum and minimum values) that the analyzed trainset would achieve during the last periodic inspection after applying the four proposed wheel set and bogie management concepts.

Table 8. Brake disc width values obtained during the last P2 periodic inspection after applying the analyzed bogie management concepts in the EN76 electric multiple unit in relation to the approach consistent with the DSU

| | No migration | Bogie rotation | Bogie swap without rotation | Bogie swap with rotation | Wheelset swap in the entire vehicle |
|---|---|---|---|---|---|
| Max dimension | 127.6 | 127.4 | 127.6 | 127.5 | 127.2 |
| Min dimension | 125.3 | 125.4 | 125.6 | 125.7 | 125.8 |
| Average | 126.42 | 126.42 | 126.42 | 126.42 | 126.42 |
| Standard deviation | 0.668 | 0.600 | 0.600 | 0.525 | 0.470 |

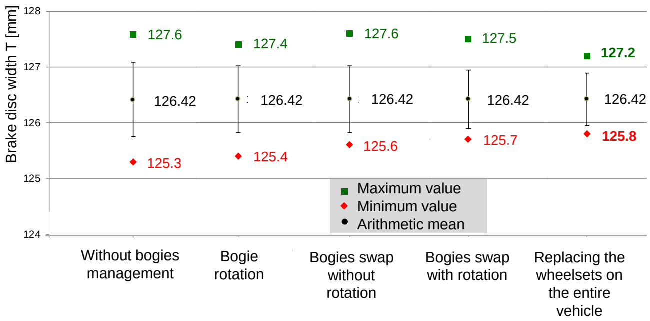


Fig. 17. Brake disc width values (maximum and minimum) obtained at the last P2 periodic inspection after applying the bogie migration in the EN76 vehicle in relation to the actual dimensions without migration

Analyzing Fig. 13, it was found that with 5 time periods allocated for bogie swapping, it is possible for all the concepts considered to increase (raise) the minimum width of one of the discs compared to the classic approach to wheel set operation in accordance with the vehicle's DSU. For the bogie swapping and rotation concept, the minimum value obtained was 125.8 mm, while 125.3 mm was achieved without bogie migration. Table 9 presents the values of the increase in the minimum dimension of the brake disc width and the percentage of material savings on the disc thickness after applying the 3 bogie management concepts.

In a qualitative (percentage) assessment, the savings associated with material recovery on the width of the smallest-sized disc ranges from 1 to 5%, depending on the concept used. Migrating wheelsets under the vehicle provides the greatest material recovery across the width of the brake discs, and therefore their thickness (0.5 mm per 10 mm over the entire 5-year period). The smallest increase was achieved for the concept of replacing wheelsets in the bogie, with a material increase of only 0.1 mm. Table 10 presents the increases in time, converted into days of use, and mileage in kilometers for the wheelset with the smallest dimension T.

Table 9. Material savings in the width of the brake disc with the highest wear for the analyzed concepts in relation to the approach without bogie migration

| | Bogie rotation | Bogie swap without rotation | Bogie swap with rotation | Wheelset swap in the entire vehicle |
|---|---|---|---|---|
| Dimension increase [mm] | 0.1 | 0.3 | 0.4 | 0.5 |
| Dimension increase [%] | 1.0 | 3.0 | 4.0 | 5.0 |

Table 10. Increase in time and vehicle mileage for the analyzed concepts of increasing the width of the brake discs T in relation to the approach without bogie migration [17]

| Concept | Minimum dimension | Day increase | Mileage increase |
|---|---|---|---|
| No migration | 125.3 mm | 0 | 0 |
| Bogie rotation | 125.4 mm | 18 | 5874 km |
| Bogie swap without rotation | 125.6 mm | 56 | 15,642 km |
| Bogie swap with rotation | 125.7 mm | 61 | 25,467 km |
| Wheelset swap in the entire vehicle | 125.8 mm | 69 | 33,219 km |

Analyzing the data in Table 10, it is concluded that the largest increase in the service life of a wheel set with brake discs and mileage is achieved using the method of migrating wheelsets under the vehicle. In the case of brake discs, the service life increased by approximately 69 days, i.e., until the next P2 inspection (approximately 33,219 km). Detailed calculations of the vehicle mileage and service life based on approximating functions (models) for each concept are given in [17]. Furthermore, this publication assesses each concept of wheel set and bogie migration in terms of technical, organizational, time, and additional costs.

## 6. Conclusions

Research into the wear and tear of wheelsets, including wheels and discs, has confirmed that brake discs wear faster than wheels. Brake discs reach 70–90% wear within five years of use, while railway wheels are only 30–40% worn. It's understandable to extend the P4 overhaul period by another year to six years to allow the wheels to achieve greater wear and tear and reach 1 million kilometers. The experience of one rail operator showed that extending the overhaul period by another year did not allow the vehicles to reach the aforementioned 1 million kilometers. Vehicles with a one-year P4 overhaul reached a mileage of approximately 750,000 km. After five years, all discs had to be replaced due to wear reaching the wear limit. The best way to prevent disc wear from accelerating during a revision repair is to use segmented discs, allowing disc replacement at any time without having to remove the bogies from the vehicle or disassemble the sets from the bogie frame. If solid discs are still used, it is possible to implement the concept of wheel set or bogie migration.

Analysis of the implementation of four bogie or wheel set management concepts allowed for an increase (raise) in the minimum brake disc width, which was achieved by one of ten wheel sets before the P4 revision repair.

The greatest increase in vehicle service life and mileage is achieved with concepts ranked in the following order: wheel set migration under the vehicle, second – bogie swapping with rotation, third – bogie swapping without rotation, and fourth – the concept of wheel set swapping in the bogie, which, given the design capabilities of the bogie, is equivalent to bogie rotation. The increase in the minimum dimension for brake disc width, regardless of the implemented wheel management concept, depends on the number of bogie swap intervals. The greater the number of swap intervals, the greater the increase in the minimum dimension for brake disc width T (from 0.1 to 0.5 mm).

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## Nomenclature

| | |
|---|---|
| DSU | maintenance system documentation |
| ECM | entity in charge of maintenance |
| ELF | electric low floor |
| ED | electro-dynamic brake |
| EP | electro-pneumatic brake |
| PN | pneumatic brake |
| P2 | periodic inspection (level two) |
| P4 | revision repair (fourth level) |

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