ARCHIVES OF TRANSPORT
Volume 54, Issue 2, 2020

ISSN (print): *0866-9546*
e-ISSN (online): *2300-8830*
DOI: *10.5604/01.3001.0014.2622*

EFFECTIVENESS ASSESSMENT OF DIESEL LOCOMOTIVES OPERATION WITH THE USE OF MOBILE MAINTENANCE POINTS

Maciej SZKODA[1], Magdalena SATORA[2], Zbigniew KONIECZEK[3]

[1,2] Cracow University of Technology, Institute of Rail Vehicles, Cracow, Poland

[3] NEWAG S.A., Nowy Sącz, Poland

Abstract:

Based on the example of 6Dg type diesel locomotives, the paper presents a new maintenance strategy concerning periodical checks at the P1 maintenance level. Currently, such locomotives are sent off to service points every 102 hours of operation or every 14 days for a P1 level check. Studies demonstrate that the average distance to be covered by a locomotive to arrive at a service point is in excess of 60.0 km, and the quantity of fuel consumed is more than 88 litres. It is costly and time consuming to have locomotives out of service and considerable resources of the railway carrier are engaged which could be made use of in the transport process. The aim of the newly developed strategy of P1 checks is to eliminate the need for locomotives to exit their routes to reach rolling stock maintenance points. The control/diagnostic and maintenance activities specified in the Maintenance System Documentation will be performed by so-called mobile maintenance points. The development of the new strategy required: identification of the current condition of the maintenance system, development of the concept of a new strategy of P1 maintenance checks, conduct of studies and operational analyses for SM42 series locomotives, performance of a durability, reliability analysis, assessment of safety together with an analysis of the risks involved in the proposed changes. In order to review and assess the efficiency of the new strategy, an observed operation of selected locomotives was conducted together with a railway carrier. During the study, the maintenance activities and processes were monitored and the costs of P1 checks were recorded. The analysis of efficiency of the new strategy of performing P1 checks without the need for a locomotive to exit its route to reach a rolling stock maintenance point demonstrated that depending on the distance covered by the locomotive to reach a maintenance point, the unit costs of a P1 level check are lower by up to 67.1% compared with the currently applied method.

Keywords: *maintenance strategy, mobile maintenance points, railway vehicles*

To cite this article:

Szkoda, M., Satora, M., Konieczek, Z., 2020. Effectiveness assessment of diesel locomotives operation with the use of mobile maintenance points. Archives of Transport, 54(2), 7-19. DOI: https://doi.org/10.5604/01.3001.0014.2622

Contact:

1) maciej.szkoda@mech.pk.edu.pl[https://orcid.org/0000-0002-9511-2253], 2) magdalena.satora@uek.krakow.pl [https://orcid.org/0000-0002-7676-4109]

1. Introduction

The subject of the paper is an assessment of the introduction of a new strategy for periodical checks at the P1 maintenance level for SM42 6Dg diesel locomotives. Currently, such locomotives are sent off to service points every 102 hours of operation or every 14 days for a P1 level check. SM42 6Dg locomotives are modern rolling stock manufactured by NEWAG S.A., where modern on-board diagnostics solutions are applied. Excluding the modernised locomotives from the traffic in order to carry out the P1 inspection is costly and involves significant resources of the carrier, which could be used in the transport process.

Projects to improve the efficiency of the process of operation railway vehicles by changing the preventive maintenance, are amongst the core areas of the strategies pursued by rail transport companies. This is due to the fact that the costs of preventive maintenance are up to 30.5% of the Life Cycle Costs (LCC) of rail vehicles and are the second cost category after the costs of power or fuel (Babeł and Szkoda 2016, CUT 2016, CUT 2017, Szkoda and Tułecki 2017, Szkoda and Satora 2019). Construction or optimisation of rail vehicle maintenance strategies are also described in professional writings. For example paper Soh, et al. (2012) presents a method of setting the optimum maintenance plan intended to minimise the total maintenance costs and the scope of maintenance activities. The solution can be applied to vehicles, infrastructure, rail traffic control systems. Matusevych, Kuznetsov and Syvchenko (2018) point that increase of maintenance system effectiveness can be generally reached in three main interdependent directions (technical, economic, organizational) that demands to work towards the following main objectives: improvement of maintenance strategy of equipment, improvement of operational and repair documentation or improvement of the organization of maintenance. Wu and Lin (2016) demonstrate that changes in the maintenance plan of a railway vehicle may consist in reducing the frequency of individual inspections and periodic repairs, i.e. extending the duration of intervals between them. Gill (2017) presents the problem of optimising the maintenance system of selected tram elements account being taken of the risk involved. The costs of dealing with the risk and the values of risk reduction achieved as a result of avoiding damage to the elements of the object have been assumed as components of the objective function. Pietrzyk and Uhl (2005) indicate that reliability analysis facilitates analysis and risk management in operation. One of the methods which can be used for this purpose is the RCM (Reliability Centered Maintenance) method, which combines analyzes related to safety, reliability and costs. The authors presented its application for the optimization of railway equipment maintenance. Cheng and Tsao (2010), Cheng et al. (2006) emphasize that safety should be the most important factor taken into account when choosing a maintenance strategy for railway vehicles. In turn, Ten and Ghobbar (2013), using three types of performance indicators related to reliability, availability and maintenance costs, the authors describe a method for changing the times to repair of rail vehicles. The method has been implemented in order to reduce the maintenance costs of rolling stock for the Dutch carrier. The authors point to the proper identification of the sub-assemblies affecting the maintenance strategy. In turn, Magiera (1982) notes that already at the time of implementation of a maintenance strategy, there is a trend towards an increase in the mileage between particular maintenance activities. Park, et al. (2011), Yun, et al. (2012), as part of the criteria for selecting the appropriate maintenance strategy, the Life Cycle Cost (LCC) and the technical availability index are taken into account when determining the maintenance intervals for assemblies and sub-assemblies of a railway vehicle.

The aim of this paper is to assess the effectiveness of introducing a new P1 maintenance strategy for SM42 series locomotives without the need to go to repair and maintenance points. It is envisaged that the control and diagnostic and maintenance activities specified in the Maintenance System Documentation (DSU) for P1 level checks would be carried out in the range of 200 moto hours instead of 102 hours, or 21 calendar days instead of 14 days, by traction teams, examiners and so-called mobile maintenance points without the need to go down to the rolling stock maintenance points.

2. Characteristics of research object – 6Dg diesel locomotive

In 2007 NEWAG S.A. company performed prototype modernisation of the 6D diesel engine which has been used in Poland for over forty years. 6D is the most common series of locomotives in Poland (in December 2019 there were 599 such vehicles). The main job of the locomotive is shunting manoeuvres at hump yards. In 2009, after two-year testing of the prototype vehicle, the first modernised locomotive was delivered to PKP Cargo S.A., the biggest Polish rail carrier. After the modernisation the locomotive was given the symbol 6Dg (Figure 1a). The modernisation scope included the replacement of the a8C22 diesel engine used till then by a new 12-cylinder C27 Caterpillar diesel engine, of 653 kW power (since 2010 of 708 kW power), meeting the exhaust emission standard according to 2004/26/WE Directive. Selected technical parameters of 6Dg locomotive are shown in Fig. 1b, and its detailed description is given in Szkoda (2017).

a)

No.	Parameter	Value
1	Axle system	Bo-Bo
2	Track gauge	1435 [mm]
3	Type of transmission	Electric AC/DC
4	Length with buffers	14240 [mm]
5	Width	3170 [mm]
6	Distance from rail head	4323 [mm]
7	On-duty mass of locomotive	70 000 [kg]
8	Fuel tank capacity	2350 [dm^3]
9	Effective power	708 kW Stage IIIB
10	Rated/idle running rotation	1800 [rpm]
11	Number of cylinders in system	V 12
12	Fuel consumption in idling	4,5 [dm^3/h]
13	Unitary fuel consumption	200 [g/kWh]
14	Diesel engine capacity	27 [dm^3]
15	Tractive force at start-up	219 [kN]
16	Maximum speed	85 [km/h]

b)

Fig. 1. a) 6Dg locomotive, b) Selected parameters of 6Dg locomotive (NEWAG S.A.)

The maintenance plan for the SM42 6Dg diesel locomotive series was specified in the Maintenance System Documentation (DSU) approved by the President of the Railway Transport Office (Table 1).

Table 1. Maintenance plan for a 6Dg SM42 diesel locomotive

No.	Maintenance level	Figure
1	P1	max.1300 km / max.102 h operation / max. 14 days
2	P2/1	max 10500 km / max 1000 mth / max 90 days
3	P2/2	21000 km / max 3000 mth / max 6 mth
4	P3	60 000 km ± 6000 km / max. 12240 mth / 20 mth ± 2 mth
5	P4	200 000 km / max. 24480 mth / 5 years
6	P5	1 000000 km / max. 122400 mth / 30 years

3. Concept of the new strategy for P1 checks

The new strategy for P1 maintenance level checks assumes that some of the activities specified in the DSU would be carried out by drivers, examiners and a mobile maintenance point without having to go to the rolling stock maintenance facility. The analysis also takes into account the possibility to change the values of the P1 interval measures according to the assumptions presented in Table 2.

Table 2. Maintenance plan for a SM42 6Dg locomotive at the P1 level

Interval measures	
Current	After the change
max 1300 km / max 102 h operation / max 14 days	max 2500 km / max 200 mth / max 21 days

The scope of the P1 maintenance activity covers a number of assemblies and subassemblies relevant for railway safety:
– body,
– underframe,
– bogies,
– castors with bearings, axle boxes and suspension for traction motors,
– drag and collision sets,
– braking and compressed air systems,
– internal combustion engine and accessories,
– propulsion systems,

– electrical machinery including: main generator, auxiliary generator, traction motor, auxiliary machinery,
– electrical circuits, apparatus and equipment,
– ventilation, air conditioning and heating,
– firefighting equipment,
– lubrication system.

The development of a new strategy for P1 checks required, *inter alia*:
– identification of the current state of play with regard to the locomotive maintenance system,
– development of a concept of a new strategy for P1 checks,
– performance of operation tests for SM42 locomotives,
– performance of a durability and reliability analysis,
– assessment of the risk involved in the proposed changes,
– assessment of the efficiency of the new maintenance strategy.

Table 3 presents an example of the activities according to the new strategy, within the P1 maintenance level for a locomotive body.

4. Maintenance checks of 6Dg locomotives according to the current strategy

Table 4 presents selected statistical data concerning failures of a 6Dg locomotive detected within P1 checks done between July 2016 and June 2017 by rail carrier. The data comprise a total of 4078 checks for 119 6Dg locomotives.

The analysis carried out showed that, from the point of view of reliability and safety of railway traffic, the significant risks detected in maintenance level P1 checks concern:

1) Electrical apparatus and equipment:
   a. damage to inverters: compressor drive, traction motor cooling fan drive – 2.97%
   b. damage to the sound signal cuffs – 3.24%
2) Vehicle body:
   c. wiper damage – 1.71%
3) Braking system:
   d. unadjusted parking brake – 9.10%
   e. damage to sandpipes – 3.15%
4) Pneumatic system:
   f. pneumatic system leaks – 5.59%

Table 3. Division of the P1 maintenance level technological process for the locomotive body

Operation/activity	Driver	Examiner	Mobile maintenance point
Bogies			
Visually inspect the bogies and check the state of attachment of its sub-assemblies.			X
Check the condition of the rail scrapers and sanding pipes		X	
Check the condition and attachment of the transverse and longitudinal force transmission elements			X
Check the condition of the springs, the screw springs and the guidance of the axle boxes		X	
Perform a visual inspection of the axle box bodies		X	
Check the condition, tightness and attachment of the hydraulic dampers			X
Check the condition and attachment of the mechanical brake components			X
Check, adjust and lubricate the brake lever system			X
Check the function of the parking brake	X		
Check and replace pad inserts			X

Table 4. Statistical data on failures detected within P1 checks

Type of failures detected in P1	Total	Percentage
Damage to inverters: compressor drive, traction motor cooling fan drive	**33**	**2.97%**
Defects in the controller of the on-board computer responsible for control and start-up	**33**	**2.97%**
Engine radiator leakage - replenishing the coolant	**196**	**17.66%**
Damage to fuel level measurement sensors	**44**	**3.96%**
Damage to driver's cab locks and door handles	**175**	**15.77%**
Defective window protection, sealing and repair of the window closing mechanism	**67**	**6.04%**
Wiper damage	**19**	**1.71%**
Damage to the windscreen washer supply hoses	**36**	**3.24%**
Damage to the sound signal cuffs	**36**	**3.24%**
Excessive wear and tear on the alternator's carbon brushes	**31**	**2.79%**
Damage to the V-belts of the radiator fan drive	**18**	**1.62%**
Damage to V-belt tensioners	**15**	**1.35%**
Damage to the sanding pipes	**35**	**3.15%**
Pneumatic system leaks	**62**	**5.59%**
Unadjusted parking brake	**101**	**9.10%**
Replacement of gaskets on 5 atm valve	**157**	**14.14%**
Hose connections for pressure gauges on the control panel	**43**	**3.87%**
Cracked exhaust manifolds	**9**	**0.81%**
TOTAL	**1110**	**100.00%**

5. Observed operation of locomotives according to the new strategy

In order to collect the data necessary to assess the effectiveness of the new P1check strategy, the operation of six 6Dg locomotives within the rolling stock of rail carrier within the company's maintenance plants (Zakład Północny and Śląski) was observed:

- SM42-1273 (Zakład Północny),
- SM42-1289 (Zakład Północny),
- SM42-1315 (Zakład Północny),
- SM42-1207 (Zakład Śląski),
- SM42-1223 (Zakład Śląski),
- SM42-1224 (Zakład Śląski).

Initially, the observed operation included a period of two maintenance cycles between maintenance level P2/1, i.e. in practice about 3÷4 months (06.2017 ÷ 09.2017, stage I) for three locomotives. After collecting and analysing the collected data and drawing up the appropriate reports, it was decided to continue the research and carry out an extended observed operation (10.2017 ÷ 11.2017, stage II and 01.2018 ÷ 02.2018, stage III), which, apart from locomotives in the Company's Zakład Północny, also comprised three vehicles in Zakład Śląski. This allowed the observation of the course of the locomotives' operation under various conditions, and thus to obtain reliable and extensive data to assess their effectiveness. The extended observed operation included one cycle between successive periodic checks at the second level of maintenance, both for the locomotives of both Zakład Północny and Zakład Śląski. The data on the time of operation and kilometrages of the surveyed locomotives are presented in Table 5.

Table 5. Time of operation and kilometrage of the surveyed locomotives

No.	Locomotive	Observed operation – stages						
		Stage I		Stage II		Stage III		Kilometrage / time of operation rate [km/mth]
		Time of operation [mth]	Kilometrage [km]	Time of operation [mth]	Kilometrage [km]	Time of operation [mth]	Kilometrage [km]	
1	SM42-1273	545	5235	279	3049	-	-	8.4
2	SM42-1289	744	4107	417	1727	-	-	
3	SM42-1315	516	5776	312	2560	-	-	
4	SM42-1207	-	-	395	1204	222	814	2.9
5	SM42-1223	-	-	400	1546	188	438	
6	SM42-1224	-	-	382	800	(no data available)	(no data available)	

No data available – no data available, operation incomplete due to locomotive stoppage in current repair

6. Assessment of the effectiveness of the new maintenance strategy

In the course of the observed operation, in addition to the measurement and control of wear and tear of assemblies and subassemblies important from the point of view of traffic safety, there was also an ongoing recording of the costs of P1 checks of selected locomotives, which was the basis for assessing the effectiveness of the new maintenance strategy.

6.1. Costs of P1 maintenance level in the current maintenance strategy

The total costs of a P1 control check done in the current strategy include:
- material and labour costs incurred at the rolling stock maintenance point ($KP1_P$);
- fuel consumption costs for a locomotive exit/arrival at P1 (KZP);
- costs of access to the infrastructure involved in the exit/arrival at P1 (KDI);
- labour costs of traction teams during the exist/arrival at P1 (KDT);
- costs of the unavailability of the locomotives exiting to P1 (KBG);
- costs of environmental charges during an exit/arrival at P1 (KOS).

6.1.1. Direct costs of a P1 check at a rolling stock maintenance point

According to the current DSU, within a time of 102 hours of operation or 14 days, 6Dg locomotives are sent to repair and maintenance points for P1 level checks. The data gathered during the observed operation indicate that the costs of a P1 check of a SM42 locomotive at a rolling stock maintenance point ($KP1_P$) are on average:

$$KP1_P = 229.45\ [PLN/check]$$

6.1.2. Costs of fuel consumption during an exit for P1

Based on the data gathered during the observed operation, the quantity and costs of fuel (KZP) consumed during exits/arrivals of selected locomotives for a P1 check were recorded. Table 6 presents an example of a record for one of the six tested SM42-1315 locomotives from Zakład Północny. Table 7 presents the total costs of fuel consumed during exits/arrivals of locomotives for P1.

Table 6. Quantity and cost of fuel consumed during exits of SM42-1315 locomotives for P1 checks (Zakład Północny)

No.	Date	Starting station	Terminal station	Distance [km]	Quantity of fuel consumed [dm^3]	Costs of fuel [PLN]
1	17.06.2017	Korsze	Olsztyn	69	30	123.00
2	26.06.2017	Iława	Olsztyn	69	40	164.00
3	03.07.2017	Jabłonowo Pom.	Olsztyn	105	75	307.50
4	10.07.2017	Jabłonowo Pom.	Olsztyn	105	95	389.50
5	17.07.2017	Braniewo	Olsztyn	100	70	287.00
6	24.07.2017	Jabłonowo Pom.	Olsztyn	105	110	451.00
7	19.08.2017	Jabłonowo Pom.	Olsztyn	105	45	184.50
8	25.08.2017	Jabłonowo Pom.	Olsztyn	105	65	266.50
9	09.09.2017	Iława	Olsztyn	69	55	225.50

Table 7. Costs of fuel consumed during exits/arrivals of locomotives for P1

No.	Nr locomotive	Exit for check [PLN]	Arrival after check [PLN]	Total costs of exits/arrivals [PLN]
Zakład Północny				
1	SM42-1273	1 836.8	1 709.7	3 546.5
2	SM42-1289	455.1	500.2	955.3
3	SM42-1315	2 398.5	3 095.5	5 494.0
4	**Total**	**4 690.4**	**5 305.4**	**9 995.8**
Zakład Śląski				
1	SM42-1207	193.1	439.0	632.1
2	SM42-1223	566.3	1 228.0	1 794.3
3	SM42-1224	487.5	583.0	1 070.5
4	**Total**	**1 246.9**	**2 250.0**	**3 496.9**

6.1.3. Costs of access to the infrastructure involved in an exit for a P1 check

Based on the observed operation, the costs were recorded of access to infrastructure (KDI) during exits/arrivals of selected locomotives at P1 checks. Table 8 presents the costs of access to the infrastructure for one of the locomotives No. SM42-1315. Table 9 presents the total costs of access to the infrastructure during exits/arrivals of selected locomotives at P1 checks.

6.1.4. Labour costs of traction teams during an exit for a P1 check

During the observed operation, the costs were recorded of the work of traction teams (KDT) during the exits/arrivals for selected locomotives for P1 checks. Table 10 presents the labour costs of traction teams during exits for one of the locomotives No. SM42-1273.

Table 11 presents the total labour costs of traction teams during the exits/arrivals of selected locomotives for P1 checks.

Table 8. Costs of access to the infrastructure during exits of a SM42-1315 locomotive for P1 checks

No.	Data	Starting station	Terminal station	Distance [km]	Train No.	Costs of access [PLN]
1	17.06.2017	Korsze	Olsztyn	69	LTS-555074	377.91
2	26.06.2017	Iława	Olsztyn	69	LTS-555115	500.52
3	03.07.2017	Jabłonowo Pom.	Olsztyn	105	TMS-514010; LTS- 155165; LSS- 555017	698.00
4	10.07.2017	Jabłonowo Pom.	Olsztyn	105	LTS-555171	698.00
5	17.07.2017	Braniewo	Olsztyn	100	LTS - 555128	402.87
6	24.07.2017	Jabłonowo Pom.	Olsztyn	105	LTS- 555081; LSS-555017	698.00
7	19.08.2017	Jabłonowo Pom.	Olsztyn	105	LTS 555045 LSS 555017	698.00
8	25.08.2017	Jabłonowo Pom.	Olsztyn	105	LTS 555245	698.00
9	09.09.2017	Iława	Olsztyn	69	LTS 555391	500.52

Table 9. Costs of access to the infrastructure during exits/arrivals of selected locomotives at P1 checks

No.	Nr locomotive	Exit for check [PLN]	Arrival after check [PLN]	Total costs of exits/arrivals [PLN]
Zakład Północny				
1	SM42-1273	2 025.8	2 806.8	4 832.6
2	SM42-1289	914.0	816.3	1 730.4
3	SM42-1315	5 271.8	5 188.0	10 459.8
4	**Total**	**8 211.7**	**8 811.0**	**17 022.7**
Zakład Śląski				
No.	**Nr locomotive**	**Exit for check [PLN]**	**Arrival after check [PLN]**	**Total costs exits/arrivals [PLN]**
1	SM42-1207	88.1	128.1	216.1
2	SM42-1223	284.3	341.4	625.7
3	SM42-1224	263.3	367.3	630.6
4	**Total**	**635.7**	**836.8**	**1 472.4**

Table 10. Labour costs of traction teams during the exits of a SM42-1273 locomotive for P1 checks

No.	Data	Staring station	Terminal station	Number of minutes	Costs of work [PLN]
1	24.06.2017	Toruń Tow.	Bydg. Wsch.	155	191.48
2	30.06.2017	Bydg. Gł. Tow.	Bydg. Wsch.	90	111.18
3	07.07.2017	Toruń Tow.	Bydg. Wsch.	190	234.71
4	10.07.2017	Bydg. Gł. Tow.	Bydg. Wsch.	130	160.59
5	18.07.2017	Włocławek Brz.	Bydg. Wsch.	215	265.60
6	26.07.2017	Kwidzyn	Bydg. Wsch.	540	667.08
7	05.08.2017	Bydg. Gł. Tow.	Bydg. Wsch.	120	148.24
8	13.08.2017	Bydg. Gł. Tow.	Bydg. Wsch.	120	148.24
9	22.08.2017	Bydg. Gł. Tow.	Bydg. Wsch.	90	111.18
10	28.08.2017	Bydg. Gł. Tow.	Bydg. Wsch.	90	111.18
11	04.09.2017	Włocławek Brz.	Bydg. Wsch.	255	315.01

Table 11. Labour costs of traction teams during the exits/arrivals of selected locomotives for P1 checks

No.	Nr locomotive	Exit for check [PLN]	Arrival after check [PLN]	Total costs exits/arrivals [PLN]
Zakład Północny				
1	SM42-1273	2 464.5	2 192.7	4 657.2
2	SM42-1289	790.6	975.9	1 766.5
3	SM42-1315	2 662.1	3 706.0	6 368.1
4	**Total**	**5 917.2**	**6 874.6**	**12 791.9**
Zakład Śląski				
No.	**Nr locomotive**	**Exit for check [PLN]**	**Arrival after check [PLN]**	**Total costs exits/arrivals [PLN]**
1	SM42-1207	292.6	913.0	1 205.6
2	SM42-1223	1 140.0	1 228.0	2 368.0
3	SM42-1224	686.0	882.7	1 568.8
4	**Total**	**2 118.6**	**3 556.1**	**5 142.3**

6.1.5. Costs of unavailability of locomotives going for P1

The performance of P1 level checks at the rolling stock maintenance points involves time wasted for the exit and arrival of the locomotive, as well as the need to provide a higher number of locomotives for shunting operations, to replace the vehicles which are not in operation. Based on the data gathered during the observed operation, a database was developed of the times of exits/arrivals of the locomotives going to P1 checks. Table 12 presents the times of exit/arrival for one of the surveyed locomotives No. SM42-1315.

Taking into account the average number of P1 control checks done in a year for one 6Dg locomotive, i.e. 34.3 checks/year, the time wasted to exit/arrive at P1 annually for the locomotive operated at Zakład Północny are 652 hours and for the locomotive operated at Zakład Śląski 453 hours.

Table 12. Time of exit/arrival of a SM42-1273 locomotive going to P1 checks

No.	Exit for P1					Arrival after P1		
	Date	Time operation ended	Time of exit for P1	Time of arrival at P1	Time P1 completed	Time of exit after P1	Time of arrival after P1	Time operation started
1	24.06.2017	06:00	09:09	09:45	11:00-13:00	13:45	13:58	14:00
2	30.06.2017	19:00	19:55	20:10	6:00-10:00 01.07.2017	19:45	21:45	22:30
3	07.07.2017	06:00	10:21	11:02	13:00-15:00	08.07.2017 g.17:29	17:42	19:00
4	10.07.2017	06:00	11:38	11:52	6:00-17:00 11.07.2017	21:11	00:29	01:50
5	18.07.2017	00:00	00:45	03:11	13:30-15:30	20.07.2017 g. 23:09	03:46	06:00
6	26.07.2017	08:30	09:05	17:01	6:30-10:30 27.07.2017	28.07.2017 g. 08:10	08:20	08:20
7	05.08.2017	16:00	17:05	17:17	6:00-17:00 06.08.2017	07.08.2017 g. 01:04	02:41	06:00
8	13.08.2017	07:00	08:35	08:46	6.30-8.30 14.08.2017	16.08.2017 g. 5:30	05:50	07:00
9	22.08.2017	07:00	07:30	08:10	9:30-13:30 22.08.2017	22.08.2017 g. 15:50	14:00	15:50
10	28.08.2017	19:00	07:15	08:15	9:30-14:30 28.08.2017	28.08.2017 g. 20:10	21:20	21:20
11	04.09.2017	03:30	04:30	13:10	13:10-14.00 05.09.2017	06.09.2017 g.3:10	05:45	06:00

The amount of losses involved in the lost opportunities and benefits involved in the locomotive being unavailable, i.e. under current repairs after a failure and in preventive maintenance done in accordance with the DSU requirements can be estimated at the cost of unavailability (KBG):

$$KBG = [T \cdot (1 - A)] \cdot KPS \quad (1)$$

where:
T – annual average time of locomotive operation [mth/year],
KPS – costs of locomotive downtime [PLN/mth],
A – technical availability ratio.

In order to assess the availability, within a specific time interval, e.g. between periodic checks, the availability ratio can be estimated from the formula:

$$A = \frac{TZ}{TZ+TN+TO} \quad (2)$$

where:
TZ – time of locomotive availability,
TN – time of locomotive unavailability due to current repairs,
TO – time of locomotive unavailability due to preventive maintenance.

Based on the 2016÷2017 operation data gathered by the carrier, the technical availability ration for a 6Dg locomotive is:
$A = 0.863$

The locomotive downtime costs (KPS) can be estimated with respect to the average consumption of fuel by the locomotive which is 8.05 [kg/mth], hence:
$KPS = 33.0\ [PLN/mth]$

The average annual time of locomotive operation is:
$T = 3916.5\ [mth]$

Based on the above assumptions, the annual costs of unavailability for a 6Dg locomotive with the current P1 check strategy are:
$KBG = [T \cdot (1 - A)] \cdot KPS = [3916.5 \cdot (1 - 0.863)] \cdot 33.0 = 17706.5\ [PLN/\text{year}]$

6.1.6. Costs of environmental charges during an exit for P1

The costs of environmental charges (KOS) during exits for a P1 check relate to the charges set by the Ministry of Environment for the emission of hazardous substances contained in exhaust gases. The level of these charges depends on the ratios published by the Ministry and is proportional to the consumption of fuel by a locomotive during an exit/arrival at a P1. With the average consumption of fuel during the exit/arrival at a P1, the costs of environmental charges are:
– for the locomotive operated at Zakład Północny:
$KOS = 2.70\ [PLN/exit]$

– for the locomotive operated at Zakład Śląski:
$KOS = 2.56\ [PLN/exit]$

6.2. Costs of a P1 level check according to the new maintenance strategy

The total costs of a P1 control check done according to the new strategy include the following:
– costs of materials and labour at the mobile maintenance point ($KP1_M$);
– costs of labour of the traction teams an examiners during P1 check activities (KDR);
– costs of fuel during arrival at a mobile maintenance point (KDM);
– costs of unavailability of the locomotives exiting for a P1 check (KBG).

6.2.1. Direct costs of P1 check at a mobile maintenance point

The direct costs of a P1 level check for a SM42 locomotive at a mobile maintenance point ($KP1_M$) are similar to those at a rolling stock maintenance point and the duration of the check should not be longer than 4 hours.

6.2.2. Labour costs of traction teams and examiners during P1 check activities

In accordance with the scope of activities involved in a P1 check, Table 13 presents the labour costs of traction teams and examiners (KDR) during a P1 check.

Table 13. Labour costs of traction teams and examiners during P1 check activities

No.	Description	Duration (minutes)	Costs of work [PLN]
1	Traction team or driver	120	148.24
2	Examiner	20	24.71
3	**Total**	**140**	**172.95**

6.2.3. Costs of fuel during arrivals at a mobile maintenance point

Based on the data gathered during the observed operation and assuming:

- average distance of arrival at a mobile maintenance point of the locomotive at Zakład Północny of 61.0 km and 19.0 km at Zakład Śląski;
- average consumption of fuel to arrive at a mobile maintenance point: 14.0 dm^3/100 km;
- net fuel costs: 4.3 PLN/dm^3;

The costs of arrival (there and back) at a mobile maintenance point (KDM) for a P1 check are:

– for the locomotive operated at Zakład Północny:
$KDM = 70{,}0\ [zł/check]$

– for the locomotive operated at Zakład Śląski:
$KOS = 21.8\ [PLN/check]$

6.2.4. Costs of unavailability of locomotives exiting for a P1 check

Elimination of significant losses of time for exits/arrivals at rolling stock maintenance points with the new P1 check strategy, of an average of 652 hours/year for a locomotive operating in Zakład Północny and 453 hours/year for a locomotive operating in Zakład Śląski, will improve the locomotive availability ratio in comparison to the current condition.

It is estimated that increased availability of the locomotive with the new strategy of P1 checks will be higher by:

- 7.94% for the locomotive operated at Zakład Północny, hence the availability ratio will increase from the current level of 0.863 to 0.9374,
- 5,65% for the locomotive operated at Zakład Śląski, hence the availability ratio will increase from the current level of 0.863 to 0.9147.

Hence the annual costs of unavailability are, respectively:

– for the locomotive operated at Zakład Północny:
$KBG = [T \cdot (1 - A)] \cdot KPS = [3916.5 \cdot (1 - 0.9374)] \cdot 33.0 = 8086.9\ [PLN/year]$

– for the locomotive operated at Zakład Śląski:
$KBG = [T \cdot (1 - A)] \cdot KPS = [3916.5 \cdot (1 - 0.9147)] \cdot 33.0 = 11023.0\ [PLN/\text{year}]$

7. Results – a comparison of the current and the new strategy

Based on the analysis it was concluded that the efficiency of the new strategy of P1 checks depends on the distance covered by the locomotive to exit/arrive at the rolling stock maintenance point. Analysing the structure of unit costs of a P1 check (Fig. 2), it can be seen that the direct costs of P1 (material and labour costs) according to the current strategy constitute only 10.7%, and the indirect costs related to fuel consumption, costs of access to infrastructure, labour costs of traction teams and the unavailability during an exit for a check as much as 89.2%. In the new P1 check strategy, the direct costs account for 36.3% of total costs.

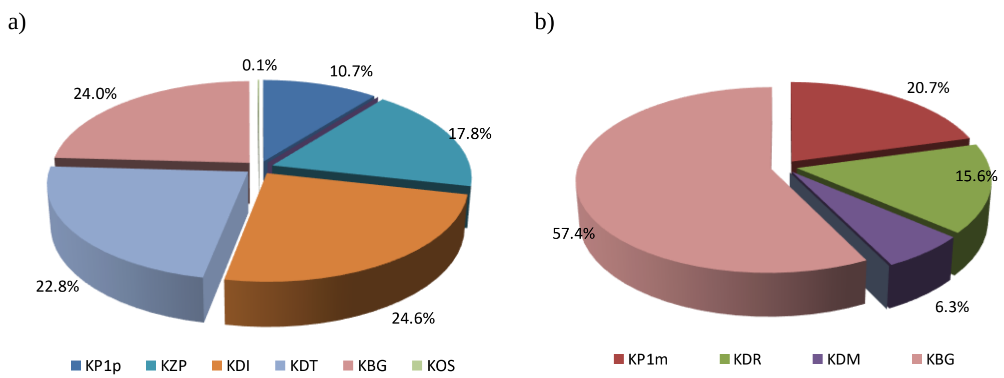

Fig. 2. Structure of unit costs for a P1 level check according to a) current and b) new strategy (labelling according to Table 14)

7.1. A comparison of costs, annually

According to the current maintenance system documentation, P1 level checks are done every 1300 km or 102 hours of operation or every 14 days, whoever is earlier. The carrier's statistical data show that during the period between July 2016 and June 2017, 4078 P1 checks were done or 34.3 checks annually per locomotive.

According to the assumptions of the new strategy for the maintenance of 6Dg locomotives, P1 level checks will be done every 2500 km or 200 hours of operation or every 21 days, whichever is earlier, which means an average of 16.5 checks in a year per locomotive (taking into account P2/1 and P2/2).

Table 14 presents a comparison of the costs of a P1 level check annually taking into account the average number of checks done in a year for both strategies for one SM42 6Dg locomotive operated at Zakład Śląski. Figures 3a and 3b present a comparison of the costs of a P1 level check annually according to the current and the new strategy for locomotives from both plants.

7.2. Comparison of the costs in the full maintenance plan

Having regard to the interval measures of the P5 maintenance level: 1000000 km, 122400 mth or 30 years, whichever occurs earlier, Fig. 4 presents a comparison of the costs of a P1 check in the full maintenance cycle for both strategies for one 6Dg locomotive operated at Zakład Północny and at Zakład Śląski.

Table 14. Comparison of the costs of a P1 check annually according to the current and the new strategy for a locomotive operated at Zakład Śląski

No.	Cost components	Label	Current strategy (PLN/year)	New strategy (PLN/year)
1	Costs of a P1 done at a maintenance point	$KP1_P$	7 870.14	0.00
2	Costs of a P1 check at a mobile maintenance point	$KP1_M$	0.00	3 785.93
3	Labour costs of traction teams and examiners during the activities involved in a P1 check	KDR	0.00	2 853.68
4	Costs of fuel during arrival at a mobile maintenance point	KDM	0.00	359.70
5	Costs of fuel during exit/arrival at a P1	KZP	12 855.64	0.00
6	Costs of access to the infrastructure involved in the exit for a P1 check	KDI	4 592.77	0.00
7	Labour costs of traction teams during an exit for a P1 check	KDT	17 695.37	0.00
8	Costs of unavailability of locomotives exiting for a P1 check	KBG	17 706.50	11 023.00
9	Costs of environmental charged during an exit for a P1 check	KOS	87.81	0,00
10		**TOTAL**	**60 808.22**	**18 022.30**

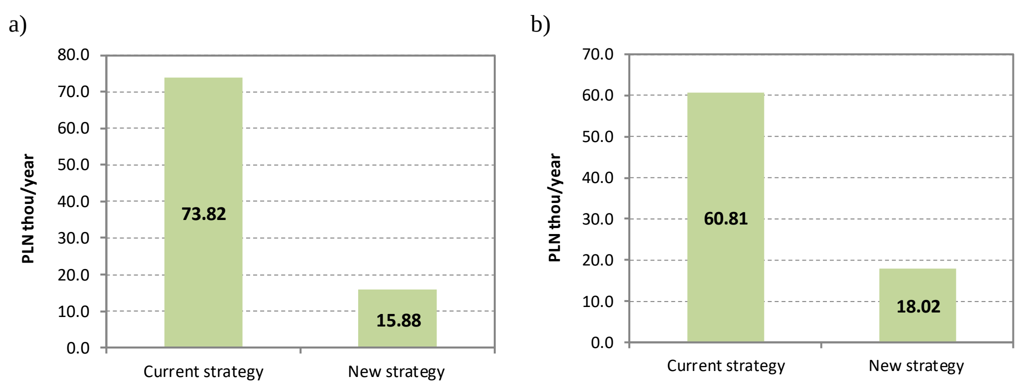

Fig. 3. Comparison of the costs of a P1 check annually at the current and the new strategies a) locomotive operated at Zakład Północny, b) locomotive operated at Zakład Śląski

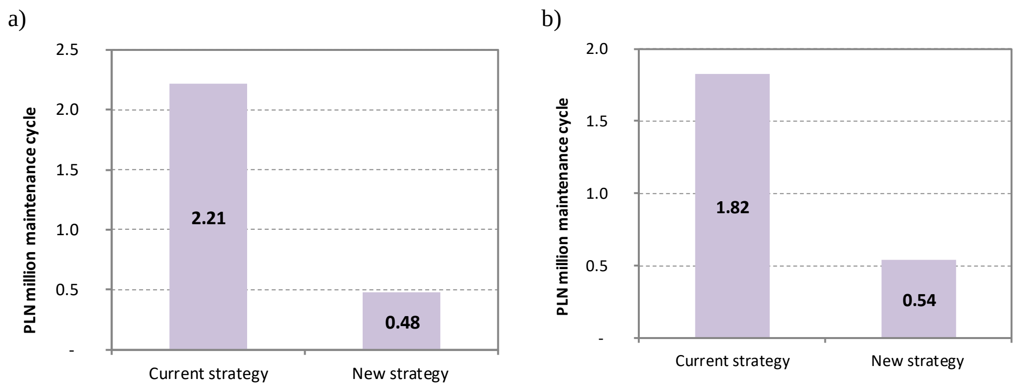

Fig. 4. Comparison of the costs of a P1 check in the full maintenance cycle at the current and the new strategies a) locomotive operated at Zakład Północny, b) locomotive operated at Zakład Śląski

8. Conclusions

The paper presents the results of the feasibility study on the project to introduce a new strategy for periodic checks at the P1 maintenance level for SM42 6Dg diesel locomotives. Generally, the new strategy consists in the performance of a technological maintenance process at the P1 level without the need to go down to rolling stock repair and maintenance points at the interval of every 200 moto-hours, 2500 km or every 21 calendar days whichever occurs earlier. The contractors of the process (operations, procedures, activities) will be traction teams, examiners and so-called mobile maintenance points. The concept of the new strategy has been subjected to research, analysis and evaluation in the following aspects: operation, combined with research and analysis of durability and reliability and effectiveness of the project. The work done demonstrated that:

– the new strategy ensures that the vehicle's availability ratio is improved by eliminating the significant loss of time for existing the route to go to maintenance points;
– the operation undertaken, observed on selected locomotives, confirms the validity of the project which has been undertaken.

The analysis of the effectiveness of the new P1 check strategy for the modernised SM42 6Dg locomotives without the need to go down to the maintenance points showed that, depending on the distance the locomotive travels to exist/go down to the maintenance point:

– the unit costs of a P1 level check for one locomotive are lower by up to 67.1% compared to the current method;
– the costs of P1 level checks, annually, for one locomotive, are lower by up to 78.5% compared to the current method;
– the costs of P1 level checks in the full maintenance cycle (30 years of operation) for one locomotive are lower by between PLN 1.3 million and PLN 1.7 million compared to the current method;
– with the full number of 6Dg locomotives in stock and assuming that all locomotives exit to rolling stock maintenance points, the annual savings are up to PLN 6.9 million.

The conducted analyses showed that it is possible to verify the maintenance plan for SM42 6Dg locomotives in the Maintenance System Documentation and to introduce records in accordance with Table 2. The next stage of work should be a safety assessment together with an analysis and evaluation of risk in order to confirm that the changes to be introduced do not violate the railway traffic safety conditions.

References

[1] BABEŁ, M., & SZKODA, M., 2016. Diesel locomotive efficiency and reliability improvement as a result of power unit load control system modernisation. *Eksploatacja i Niezawodnosc – Maintenance and Reliability*, 18, 38–49.

[2] CHENG, Y. H., & TSAO, H. L., 2010. Rolling stock maintenance strategy selection, spares parts' estimation, and replacements' interval

calculation. *International Journal of Production Economics*, 128(1), 404-412.

[3] CHENG, Y. H., YANG A. S., & TSAO H. L., 2006. Study on Rolling Stock Maintenance Strategy and Spares Parts Management. In: *7th World Congress on Railway Research - WCRR 2006 Montreal, Canada*.

[4] CRACOW UNIVERSITY OF TECHNOLOGY, INSTITUTE OF RAIL VEHICLES (CUT), 2016. *Optimisation of the plan of maintenance of ET22 electric locomotives operated by CTL Logistics Sp. z o.o.* Report no. M-8/509/2016/P, Krakow.

[5] CRACOW UNIVERSITY OF TECHNOLOGY, INSTITUTE OF RAIL VEHICLES (CUT), 2017. *Optimisation of the plan of maintenance of SM42 diesel locomotives operated by CTL Logistics Sp. z o.o.* Report no. M-8/160/2017/P, Krakow.

[6] CRACOW UNIVERSITY OF TECHNOLOGY, INSTITUTE OF RAIL VEHICLES, 2016. *Optimisation of the plan of maintenance of 440Ra cistern wagons operated by CTL Logistics Sp. z o.o.* Report no. M-8/220/2016/P, Krakow.

[7] GILL, A., 2017. Optimisation of the technical object maintenance system taking account of risk analysis results. *Eksploatacja i Niezawodnosc – Maintenance and Reliability*, 19(3), 420-431.

[8] MAGIERA, J., 1982. *Obsługa i utrzymanie pojazdów szynowych.* Kraków: Wydawnictwo Politechniki Krakowskiej.

[9] MATUSEVYCH O., KUZNETSOV V., & SYCHENKO V., 2018. The method for increasing the efficiency of equipment's maintenance in railway traction power supply systems. *Archives of Transport*, 47(3), 39-47.

[10] PARK, G., YUN, W. Y., HAN, Y. J. & KIM, J. W., 2011. Optimal preventive maintenance intervals of a rolling stock system. In: *International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering - ICQR2MSE 2011* Xi'an, China, 427-430.

[11] PIETRZYK A., & UHL T., 2005. Use of RCM methodology for railway equipment maintenance optimisation. *Archives of Transport*, 17(2), 65-83.

[12] SOH, S. S., RADZI, N. H. M., & HARON, H., 2012. Review on Scheduling Techniques of Preventive Maintenance Activities of Railway. In: *Fourth International Conference on Computational Intelligence, Modelling and Simulation (CIMSiM)*, Kuantan, Malaysia.

[13] SZKODA, M., & SATORA, M., 2019. Assessment of the permissibility of the risk of changing the strategy for the maintenance of rail vehicles based on the example of a selected locomotive type. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 233(9), 906-925.

[14] SZKODA, M., & TUŁECKI, A., 2017. Ecology, energy efficiency and resource efficiency as the objectives of rail vehicles renewal. *Transportation Research Procedia*, 25, 386-406.

[15] SZKODA, M., 2017. *Kształtowanie potencjału przewozowego przedsiębiorstw transportu kolejowego*. Kraków, Wydawnictwo Politechniki Krakowskiej.

[16] TEN, W. M., & GHOBBAR A. A., 2013. Optimizing inspection intervals – Reliability and availability in terms of a cost model: A case study on railway carriers. *Reliability Engineering and System Safety*, 114(0), 137-147.

[17] WU, J., & LIN, B., 2016. *Major Maintenance Schedule Optimization for Electric Multiple Unit Considering Passenger Transport Demand.* School of Traffic and Transportation. Beijing: Jiaotong University, Beijing.

[18] YUN, W.Y., HAN, Y.J., & PARK, G., 2012. Optimal preventive maintenance interval and spare parts number in a rolling stock system. In: *International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering - ICQR2MSE 2012* Xi'an, China, 380-384.