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Justification of the Need for Locomotive Diagnostic Systems

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ABSTRACT

In the world and domestic practices of technical maintenance and repair (TMR) of locomotives there exists a tendency for the expanded use of technical diagnostics systems, the transition to predictive repair to reduce the costs of their life cycle. Modern hardware and software tools make it possible to create automated technical diagnostics systems (ATDS) for all types of locomotive equipment but equipping service repair locomotive depots with them requires significant capital costs with an unacceptably long payback period. The objective of the work is to develop a method and a corresponding simulation modelling software program to determine technical and economic feasibility of using certain means of technical diagnostics.

Diagnostic systems reduce waiting time for repairs, the volume and cost of scheduled and unscheduled TMR, which makes it possible to reduce the operating fleet of locomotives.

In modern economic calculations, to assess the success of an investment project, the indicator «Net present value (NPV)» of the project is used. Based on this principle, in relation to ATDS, a method for determining feasibility of introducing various types of ATDS and the corresponding methodology and software made with the algorithmic language VBA (Visual BASIC for Applications) in the MS Excel environment has been developed.

The work carried out simulation modelling for Russian conditions of the payback of main types of diagnostic systems comprising on-board based microprocessor control systems, rheostat testing stations for diesel locomotives, diagnostics of traction motors, etc. The economic feasibility of introducing these systems has been proved. Also, economically inexpedient diagnostic systems have been identified, for example, automatic measurement of the profile of a wheel set tire.

Keywords: *transport, railway, locomotives, technical maintenance and repair, technical diagnostics, economic feasibility, simulation modelling.*

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1. Statement of the analysed problem

Reliable operation of traction rolling stock is the main task of its technical maintenance and repair system (TMR) [1; 2]. The organisation of TMR all over the world demonstrates a trend towards increased role of technical diagnostics systems (TDS[1,2]) [3–10]. Modern TDSs are built as automated TDS (ATDS) on the basis of hardware and software using personal computers or microprocessor control units [3–5; 16; 17]. However, the cost of ATDS is quite high.

Research carried out at NIITKD[3] regarding Russia and in relation to the conditions of one of a hundred service locomotive depots (SLD) which is «Tynda-Severnaya» [11; 12] of the Northern Latitudinal Railway of the Eastern Range (BAM) showed that the complex equipping with ATDS of a single depot will require at least Q_{KSLD} > 450 million roubles: capital costs for all SLD will exceed Q_K = 100 • 450 > 450 billion roubles. At the same time, an expert assessment makes it possible to estimate possible savings at the level of a maximum of 20 billion roubles, and in fact, no more than 10 billion roubles: the payback period of the complex technical diagnostic system will be unacceptable (450/20 > 20 years) even without discounting. Thus, feasibility of using ATDS requires an economic justification for each type of equipment with an individual assessment of economic feasibility of its implementation.

2. The proposed method and methodology for calculating the efficiency of ATDS

The main source of information about the technical condition of the locomotive is currently the on-board handwritten journal of the form TU-152 [1; 3], in which the driver records subjective comments on locomotive operation. For example, «current surges in traction», «no power at the 15th position», «no entry to recuperation mode», etc. The second equally important source of information is associated with the results of visual acceptance of the locomotive for TMR, during which the records are made on completeness of the locomotive and the presence of manifestations of vandalism, as well as on external signs of failures: oil leaks, cracks, etc. [6]. The presence of on-board ATDS will make it possible to determine pre-failure conditions (operable, but faulty) before the locomotive enters the depot. As a result, both a reduction in dangerous failures and a reduction in downtime of a locomotive in the depot for unscheduled repairs and waiting for delivery of spare parts are possible.

Reducing TMR time disengages part of the locomotive fleet: as the downtime *T* on repairs *x* decreases, the time reserve ΔT_X accumulates, which tends to become equal to operating time of a locomotive T_L:

$$T_L = \sum_{X=1}^{X} (\Delta Tx) , \qquad (1)$$

where *X* is number of repairs with time saving.

Saving downtime for repairs will reduce the number of purchased locomotives in the volume N_L:

$$N_L = \sum_{y=1}^{Y} (\Delta Ty) / T_L , \qquad (2)$$

where *Y* is total number of time-saving repairs due to ATDS.

The first type of savings from introduction of ATDS will be R_1:

$$R_1 = C_L \cdot T_L, \qquad (3)$$

where C_L is cost of a locomotive.

The second effect R_2 will be achieved from a reduction in the cost of repairs based on the more exact choice of elements to be repaired according to the actual technical condition [4–6]. The term «predictive» maintenance is often used. Pic. 1b shows the dynamics of obtaining the effect R_2. At each repair *i*, due to the absence of necessity to perform part of the scheduled preventive work, the effect ΔR_{2i} will be achieved. It should be borne in mind that repair *X* may require enhanced repair, which will lead to an increase in the cost of TMR by the amount of ΔR_{2X}. Effect of predictive repair:

$$R_2 = \sum_{i=1}^{X-1} (\Delta R2i) - \Delta R_{2X} . \qquad (4)$$

The effect is achieved under the condition that:

$$\sum_{i=1}^{X-1} (\Delta R2i) < \Delta R_{2X} . \qquad (5)$$

The third type of R_3 effect from TDS is prevention of expensive failures by eliminating pre-failure. For example, restoring the pre-

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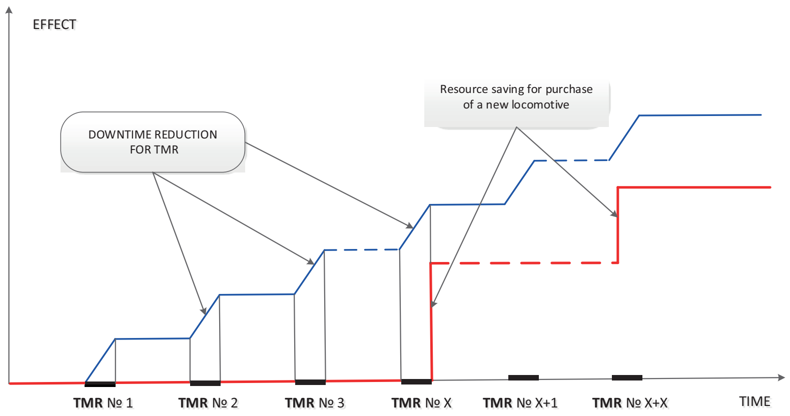
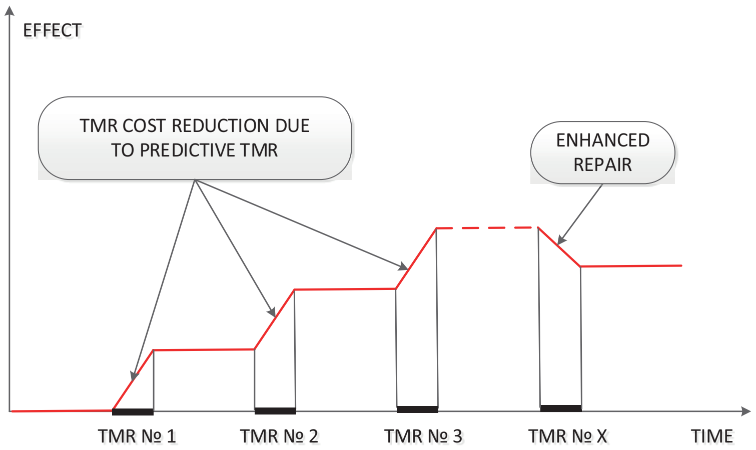
[1] GOST [state standard] 20911-89. Technical diagnostics. Terms and definitions. [Electronic resource]: http://docs.cntd.ru/document/1200009481. Last accessed 21.12.2020.

[2] GOST [state standard] 27.002-2015. Reliability in equipment (SSNT). Terms and definitions. [Electronic resource]: http://docs.cntd.ru/document/1200136419. Last accessed 21.12.2020.

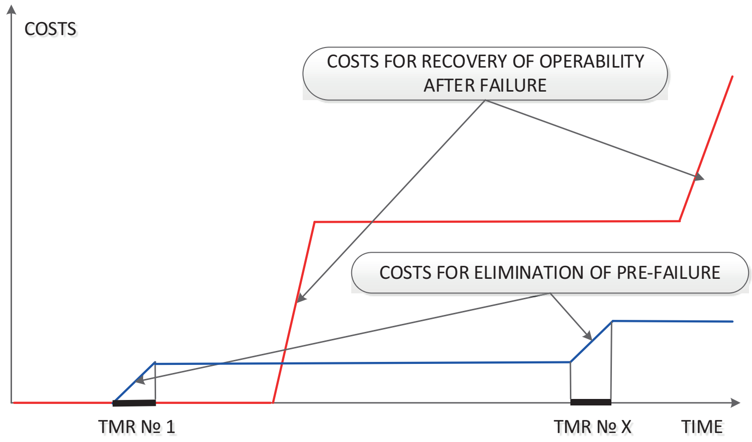
[3] Official website of NIITKD. [Electronic resource]: http://niitkd.com. Last accessed 21.12.2020.



a – R_1 from reduction of the locomotive fleet.



b – R_2 from predictive maintenance.



c – R_3 from decrease of consequences of failures.

Pic. 1. Effect R from application of TDS (compiled by the authors).

Table 1

Overhaul mileage of locomotives for calculating NPV [1]

Series	IR	TM-1	TM-2	TM-3	TM-4	CR-1	CR-2	CR-3	LO	HR[1]
ES5K	200	0,400	2,4	–	300	30	300	600	1200	2400
ES4K	180	0,200	1,67	–	300	30	300	600	1200	2400
TE10MK	120	0,175	3,5	7,2	300	29	115	210	720	1420
2TE25KM	150	0,175	3,5	15	300	75	300	600	1200	2400

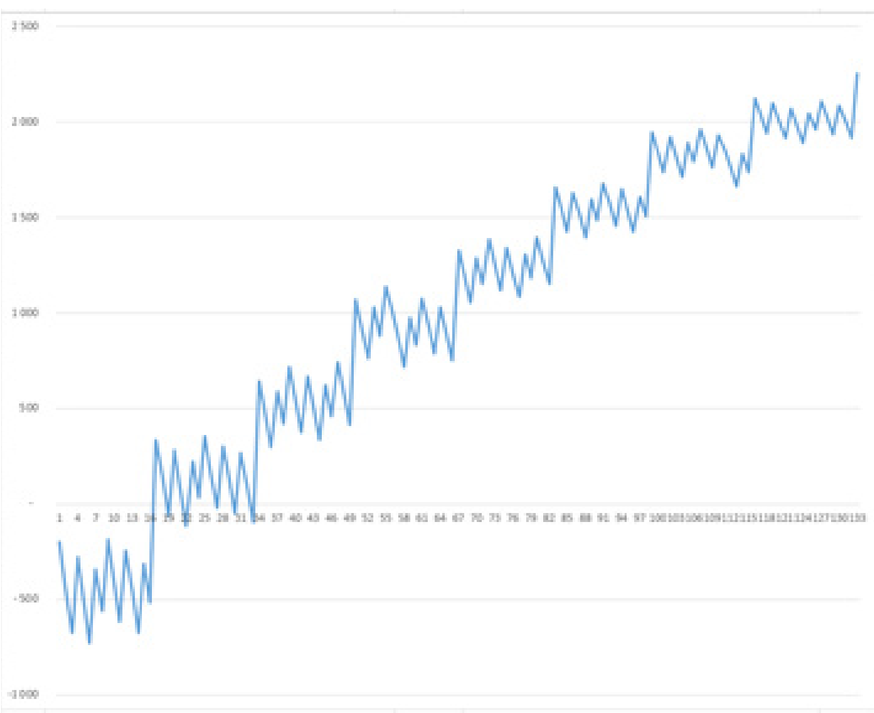
Table 2

Estimated downtime for TMR by series, minutes (compiled by the authors)

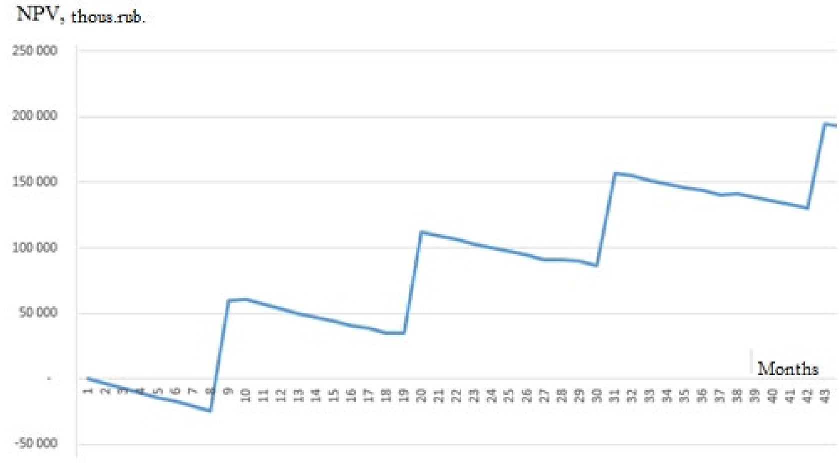
	IR	TM-2	CR-1	CR-1+TM-4	CR-2	CR-3	HR	TM-4	TM-3
VL80R	741	85	2106	2552	5590	14542	12247	1026	
SKO	2757	24	1620	1708	1458	4971	6817	1068	
Kvar	3,72	0,28	0,77	0,67	0,26	0,34	0,56	1,04	
N	560	4695	23	168	13	6	8	22	
VL80S	740	78	2183	2239	4907	11592	42181	864	
SKO	2765	24	2142	1581	1827	4384	11854	928	
Kvar	3,74	0,31	0,98	0,71	0,37	0,38	0,28	1,07	
N	583	4382	57	182	11	7	6	58	
2ЭС5К	964	100	1500	3390	4139	7130	0	962	
SKO	3093	28	1056	2530	2232	4441		979	
Kvar	3,21	0,28	0,70	0,75	0,54	0,62		1,02	
N	304	3710	89	38	9	11	0	46	
3ES5K	945	90	1850	2217	4564	10877	0	1713	
SKO	3053	24	933	2189	3197	3360		3744	
Kvar	3,23	0,27	0,50	0,99	0,70	0,31		2,19	
N	263	3718	110	70	18	10	0	46	
2ES4K	1567	93	5880	14282	14826	18776	0	6227	
SKO	16523	31	6654	2127	5581	9196		4916	
Kvar	10,54	0,34	1,13	0,15	0,38	0,49		0,79	
N	404	3323	59	2	5	9	0	10	
3ES4K	789	109	4856	0	7124	25939	0	6395	
SKO	3681	58	9260		2825	10821		9387	
Kvar	4,66	0,54	1,91		0,40	0,42		1,47	
N	675	1704	134	0	16	9	0	36	
2TE10MK	2146	81	8971	10526	19230	29295	31435	2730	3064
SKO	17617	55	5290	10178	11795	15717		6356	3961
Kvar	8,21	0,68	0,59	0,97	0,61	0,54		2,33	1,29
N	608	4068	46	13	11	7	1	45	88
3TE10MK	1278	93	8526	7466	24317	13796	13386	3568	6033
SKO	5212	23	6303	5186	7030	4549	13479	3871	7303
Kvar	4,08	0,25	0,74	0,69	0,29	0,33	1,01	1,08	1,21
N	1100	4648	61	15	13	4	5	21	78
2TE116U	1172	73	4581	3329	12452	15284	0	997	2615
SKO	4027	19	8871	2267	4964	2638		1227	3344
Kvar	3,44	0,27	1,94	0,68	0,40	0,17		1,23	1,28
N	459	2664	36	13	10	9	0	35	161
2TE25KM	2295	77	2890	2871	11274	106	0	2416	1813
SKO	15550	18	2673	957	2571			3135	2051
Kvar	6,78	0,23	0,93	0,33	0,23			1,30	1,13
N	437	3126	60	7	12	1	0	48	244

[1] IR is for initial repair, TM – for technical maintenance, TR is for current repair, LO is for light overhaul, and HR is for heavy repair (overhaul). – Ed. note.

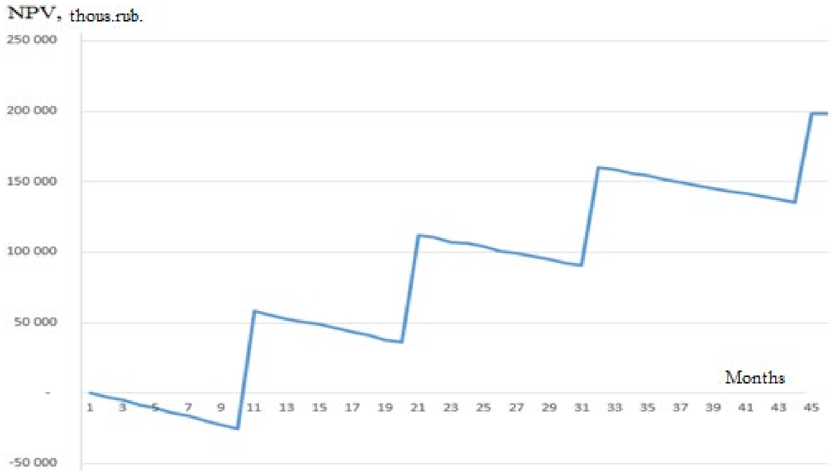
	B	C	D	E	F	G	H
1	MPSU						2 254
2	1	2	3	4	5	6	7
3	Year	Month	R	Mileage, thous. km	Costs, thous. rub.	Effects, thous. rub	NPV
4	0	0	1,000	-	- 200,000	-	- 200
5	0	1	0,992	12,167	- 290,000	53,104	- 435
6	0	2	0,984	23,967	- 285,500	44,253	- 672
7	0	3	0,976	35,798	- 294,500	697,609	- 279
8	0	4	0,969	45,968	- 273,500	44,253	- 501
9	0	5	0,961	57,826	- 290,000	53,104	- 729
10	0	6	0,953	69,626	- 294,500	697,609	- 344
11	0	7	0,946	79,796	- 272,000	44,253	- 560
12	0	8	0,938	91,657	- 296,000	697,609	- 183
13	0	9	0,931	101,823	- 273,500	44,253	- 396
14	0	10	0,924	113,681	- 288,500	53,104	- 614
15	0	11	0,916	125,484	- 294,500	697,609	- 244
16	0	12	0,909	135,654	- 283,500	44,253	- 462
17	1	1	0,902	147,512	- 288,500	53,104	- 674
18	1	2	0,895	159,316	- 294,500	697,609	- 313
19	1	3	0,888	169,486	- 273,500	44,253	- 517
20	1	4	0,881	181,343	- 303,500	1 272,371	336
21	1	5	0,874	191,078	- 270,500	44,253	139
22	1	6	0,867	202,943	- 288,500	53,104	- 65
23	1	7	0,860	214,746	- 294,500	697,609	281
24	1	8	0,853	224,916	- 273,500	44,253	86
25	1	9	0,846	236,774	- 288,500	53,104	- 113
26	1	10	0,840	248,577	- 294,500	697,609	225
27	1	11	0,833	258,747	- 273,500	44,253	34
28	1	12	0,826	270,605	- 306,000	697,609	358
29	2	1	0,820	280,771	- 272,000	44,253	171
30	2	2	0,813	292,633	- 290,000	53,104	- 22
31	2	3	0,807	304,413	- 294,500	697,609	304



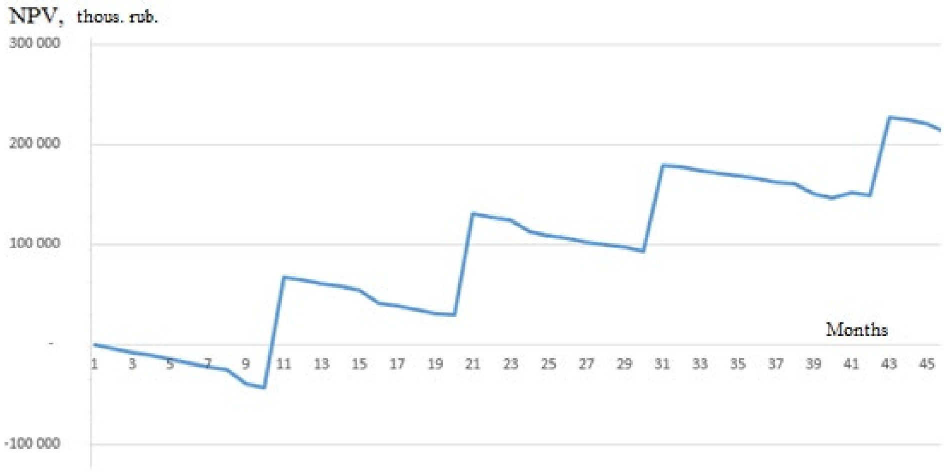
Pic. 2. Results of simulation of NPV of a TDS (compiled by the authors).



a – MCDS of AC locomotives of series ES5K with reversible converter.

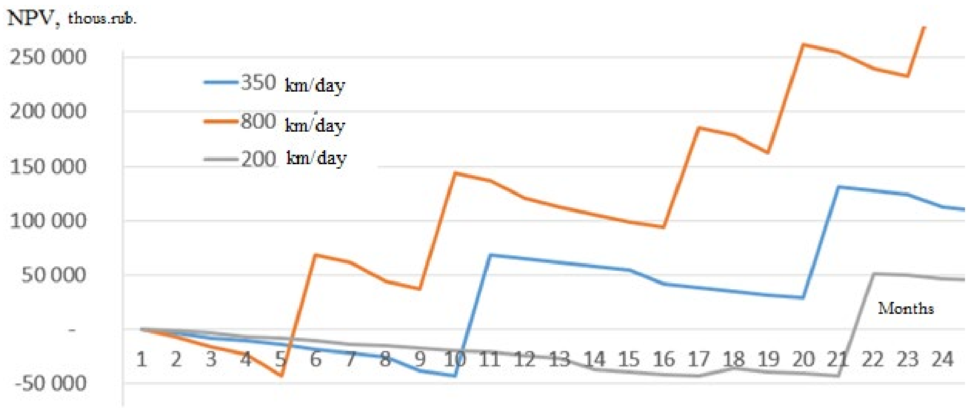


b – MCDS of DC locomotives of series ES4K.

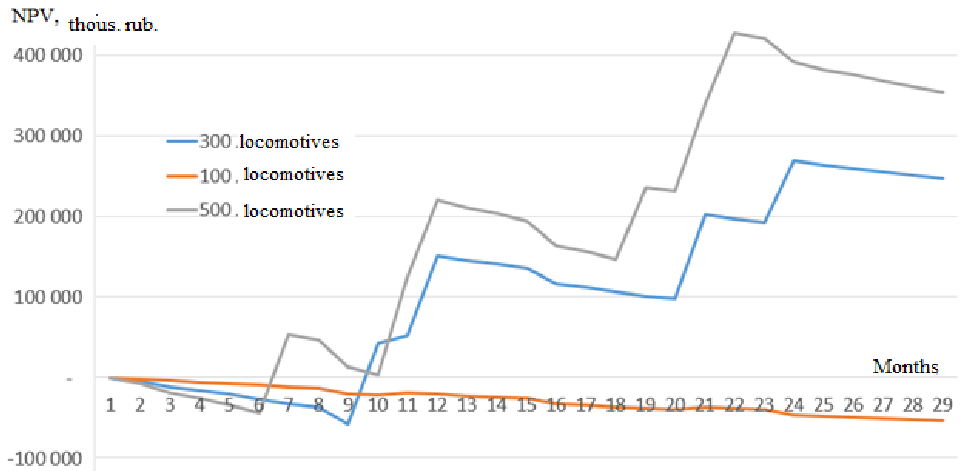


c – MCDS of diesel locomotives of series 2TE25KM.

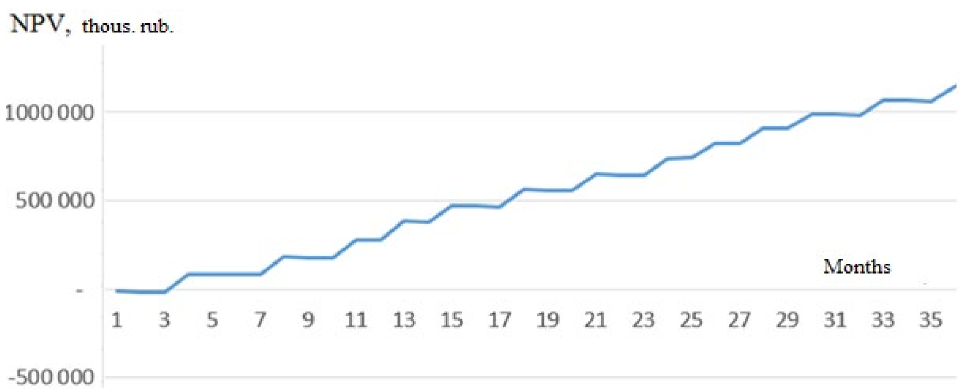
Pic. 3. Results of calculation of NPV for on-board diagnostics based on MCS (compiled by the authors).



a – average daily mileage.

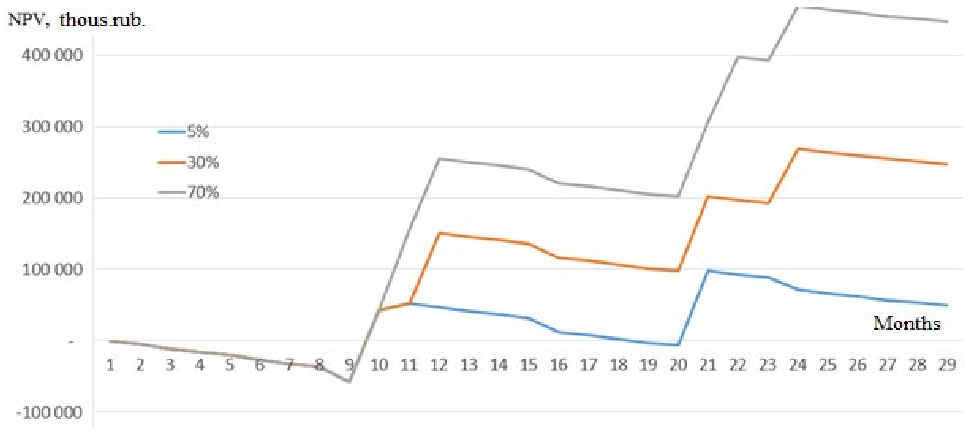


b – serviced locomotive fleet.



c – reduction of number of failures (units per 1 mln km mileage).

Pic. 4. Influence of initial data on NPV result at the example of a MCDS of diesel locomotives (compiled by the authors).



Pic. 5. Results of calculation of NPV for a rheostat test station (compiled by the authors).

failure state of a diesel cylinder cover can prevent cracks with further rejection of the cover. At the same time, the number of elimination of pre-failures may exceed the number of failures, but the total cost of unscheduled repairs will decrease:

$$R_3 = R_{FAIL} - \sum_{n=1}^{N} (R_{PRE\text{-}FAIL\ n}), \qquad (6)$$

where n is next elimination of the pre-failure state;

N is total number of eliminations of pre-failure states;

$R_{PRE\text{-}FAIL\ n}$ is cost of elimination of the n-th pre-failure;

R_{FAIL} is cost of elimination of failure and recovery of operability.

The costs of TDS are made up of capital costs for purchase, installation and launch of TDS in operation (Q_K), and the current costs of operating TDS (Q_E), consisting of the salary fund of diagnosticians, the cost of energy resources, metrological and other types of services.

In the program for modelling the efficiency of TDS, the indicator «Net present value of the project NPV» [13] is used, according to which the investment project is expedient if the positive value of $NPV > 0$ for the time t which is less than the specified one. The program is implemented by the authors in the algorithmic language Visual Basic for Applications (VBA) in MS Excel [14].

When calculating *NPV*, time t is usually taken as an integer over the years. The developed program proposes to represent the discounting process as a continuous process of integration:

$$NPV = -Q_K + \int CF(t)(1+R)^{-t}\,dt, \qquad (7)$$

where Q_K are capital costs for acquisition and implementation of TDS.

$CF(t)$ is cash flow at time t;

R is annuity discount factor.

In the program, formula 7 is implemented as double summation:

$$NVP = -Q_K + \sum\sum (ZE_{ym} - ZC_{ym}) \cdot 1{,}1^{-(y + m/12)}, \qquad (8)$$

where y is year cycle from year zero to tenth: y Є [0, 10];

m – cycle for 12 months of each year: m Є [1, 12];

ZE_{ym} and ZC_{ym} – effect and costs obtained in the y-th year and m-th month.

The effects and costs are associated with planned and unscheduled TMR, the time of which depends on the locomotive mileage, which is determined in the program by a given average daily mileage, considering downtime for repairs.

Q_E operating costs for locomotive maintenance are set as: salary of diagnosticians, rent of premises and other fixed costs, unit costs of diagnostics (consumption of electricity, materials, fuel, oil, and other items of expenditure).

When simulating, standard overhaul runs are set (Table 1), since they are strictly regulated: overruns of locomotives are unacceptable for safety of train traffic, and underrun leads to additional costs for TMR. The frequency of TM-1 and TM-2 in km was recalculated based on hours according to the average daily mileage of the locomotive (Table 1).

Time for TMR of all types of locomotives is normalized, but the actual downtime is much longer. For example, 2TE10MK during CR-1

Table 3

Locomotive fleet reduction percentage when using ATDS (compiled by the authors)

ATDS	Locomotive series	Fleet reduction, %
On-board ATDS based MCDS (MSUD type)	ES5K	2,8 %
On-board ATDS based on MCDS (MPSU type)	ES5K	2,8 %
On-board ATDS based on MCDS (MSU-TP type)	2TE25KM	3,3 %
On-board ATDS based on APC BORT (hardware-software complex BORT)	2TE25KM, 2TE116U, TE10MK	1,0 %
Rheostat test station (Rheostat)		12,5 %
Vibration diagnostics WMU (Vibro)	ES5K	3,0 %
TEM test stand (TEM)	ES5K	0,5 %
System for measuring the profile of wheel set tires (WS)	ES5K	0,0 %
ATDS «Doctor»	ES5K	0,7 %

Table 4

Percentage of the total effect of reduced downtime for TMR when using ATDS (compiled by the authors)

ATDS	TM-1	TM-2	TM-3	TM-4	CR-1	CR-2	CR-3	LO	HR	IR
MCDS (MSUD type)	16,6 %	23,1 %			44,8 %					15,5 %
MCDS (MPSU type)	20,3 %	16,9 %			49,4 %					13,4 %
MCDS (MSU-TP type)	19,6 %	5,7 %	34,4 %		1,3 %					39,0 %
APC Bort			67,9 %		2,5 %					29,6 %
Rheostat			48,4 %		21,6 %	11,6 %	7,8 %	2,1 %		8,6 %
Vibro					65,9 %					34,1 %
TEM							26,3 %	22,5 %	11,3 %	39,9 %
WS				3,6%	96,4 %					

Table 5

NPV of ATDS for one depot with the fleet of 200–300 locomotives (compiled by the authors)

ATDS	Payback period, months	Payback period, years	NPV for 3 years, mln rub.	NPV for 6 years, mln rub.
MCDS (MSUD type)	8	0,67	141	251
MCDS (MPSU type)	10	0,83	150	266
VCDS (MSU-TP type)	10	0,83	162	357
Rheostat	3	0,25	1 144	2 020
Vibro	11	0,91	251	385
TEM	14	1,17	6	75
WS	-	-	-10	-13
Doctor	32	2,67	43	80

at a rate of 36 hours spends an average of 150 hours, and during CR-2 at a rate of four days it spends 13 days. Therefore, in the simulation, real downtime was taken for series of locomotives, calculated by the authors by processing data from the information system of JSC Russian Railways ASOCT (automated system for operational control of trains). Table 2 shows the results of the calculation. For each series of locomotives, for each type of repair and maintenance works according to ASOCT data, the mathematical expectation of downtime M, the standard deviation σ and the coefficient of variation Kvar = σ/M were calculated [15].

The downtime at TM-2 was most predictable (unimodal): $M = 86$ minutes, $\sigma = 11$, Kvar = 0,13, which is largely explained by the procedure adopted at JSC Russian Railways for changing the state of TM-2 to unscheduled repairs (UR) when the idle time is exceeded. A large scatter occurs for unscheduled repairs ($M = 1199$ minutes, $\sigma = 572$, Kvar = 0,48) and wheel set turning ($M = 2475$ minutes, $\sigma = 2024$, $Kvar = 0{,}82$). Thus, the downtime for all types of TMR (except for TM-2 at locomotive maintenance points – LMP) has a wide spread, which requires an individual approach when entering the initial data in the simulation.

The simulation results are presented in the form of a table and a graph of NPV changes by months (Pic. 2).

3. Modelling the effectiveness of TDS application

On-board diagnostics is performed based on standard microprocessor control systems (MCS), so the diagnostic functionality is «free». Capital costs Q_K include creation of an automated workplace (AWP) for the diagnostician, AWP purchase and maintenance. Operating costs are mainly related to the salaries of diagnosticians.

The effect of on-board diagnostics is when accepting a locomotive (TM-1), at a LMP (TM-2). When performing TM-3 and CR-1, deep diagnostics are carried out. To do this, MCS data on operation of the locomotive are entered into a stationary computer (via a radio channel, from a flash drive, via Wi-Fi, etc.) for diagnostics using specialized software (AWP MCS): hidden defects and pre-failures are revealed. During «heavy» types of TMR, the diagnosis of MCS is not required. The effect of MCS is achieved by reducing TMR time, and most importantly, by preventing unscheduled repairs by eliminating them at the pre-failure stage. The main cash flow is due to reduction in locomotive fleet required for transportation. The main operational cost item is the salary of diagnosticians.

Pic. 3 shows the result of modelling for three mass types of MCS: MCDS (microprocessor control and diagnostic system) of AC electric locomotives with reversible converters (locomotives of E5K, 2ES5K, 3ES5K, 4ES5K, EP1, EP1M, EP1P series), MCDS of DC electric locomotives of 2ES4K, 3ES4K series, and MCDS of diesel locomotives of 2TE116U, 2TE25KM, 3TE25KM series. The discounted payback period of the diagnostic system based on MCS is less than a year. Sharp upward jumps in Pic. 3 and further correspond to reduction of the locomotive fleet by one unit.

Modelling showed high sensitivity of the model to some initial parameters and low sensitivity to others (Pic. 4). The average daily mileage has a great influence (Pic.4a), a decrease in which can make ACDS unprofitable due to the rare TMRs while maintaining current costs. The number of serviced locomotives has a similar effect (Pic. 4b). The main effect is achieved by reducing the number of unplanned repairs (Pic. 4c). To a lesser extent, the cost of restoring serviceability of the locomotive and the salary of diagnosticians affect the model.

The main effect of almost all CDSs was reduction of the locomotive fleet. And, conversely, CDSs that do not give this effect turned out to be unprofitable.

Pic. 5 shows the results of modelling NPV of rheostat test stations of a diesel generator unit of diesel locomotives. The economic effect is defined as the losses incurred by the locomotive department in the absence of rheostat tests: the number of unscheduled repairs will increase significantly, the number of locomotive returns to the depot by the representative of Russian Railways will increase. Despite the high cost of the station, its recoupment occurs within a few months, since the absence of rheostat tests will lead to a significant increase in expensive diesel generator unit failures.

The effect of vibration diagnostics is to eliminate unscheduled repairs due to failures of wheel-motor units (WMU), reduce the volume of current repairs in the absence of comments on the technical condition of WMU. Traction electric motors (TEM) testing stations by the mutual load method are used after «heavy» types of repairs: CR-3, LO and HR. Testing engines allows checking their serviceability and permits to exclude corresponding failures during operation. In addition, reading of the characteristics of the traction electric motor makes it possible to select them and exclude additional failures due to spread of the characteristics of the traction electric motor. Negative NPV was obtained for the automatic wheel set profile measurement system. The results of the performed NPV calculations are shown in tables 3–5.

Conclusions.

1. The practical application of ATDS requires a feasibility study (FS), since, in general, their payback is equal to tens of years.

2. When choosing the type of ATDS, preference should be given to on-board and built-in ATDS. In case of their inexpediency preference should be given to portable and stationary ones.

3. A method for assessing the technical and economic feasibility of introducing various types of ATDS and the corresponding software in the algorithmic language VBA in the MS Excel environment has been developed. The method of calculating the indicator «Net present value of the project» is taken as a basis.

4. The modelling of the payback of main types of ATDS was carried out with a factor analysis of influence of various parameters (fleet size, average daily mileage, failure rate, reduction in the number of failures).

5. Modelling has shown the economic feasibility of the following ATDS: onboard ATDS based on standard microprocessor control systems, specialized onboard ATDS for diagnosing diesel generator units for diesel locomotives without MCS, rheostat testing stations for diesel generator units of diesel locomotives, vibration diagnostics of wheel-motor units (WMU), diagnostics and testing of VIP thyristors, portable systems for diagnosing electrical equipment.

6. Modelling has showed the lack of economic effect from introduction of several ATDSs, including automatic check of the profile of the tyre.

7. The main type of effect from introduction of ATDS is reduction in the operated fleet of locomotives.

8. Reduced repair time has a significant impact on the efficiency of ATDS. The cost of restoration of operability and the initial cost of ATDS have a relatively low impact.

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