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RESEARCH OF IMPACT OF THE LOADING ON ENDURANCE OF THE FREIGHT LOCOMOTIVE ENGINES

Summary. The publication reflects the research results of the rationalization of the rolling stock use of JSC LG Lithuanian railways to increase the reliability indicators of the freight diesel locomotive exploitation reliability. The comparative evaluation of the exploited freight diesel locomotive work duration, according to the technical documentation, by using comparative test results and indirect diesel reliability criteria approved in practice. An algorithm of work duration forecasting methodology has been created, as well as a programme complex of mathematic modelling. The differences of the results indicated in the experiment and modelled by computer do not exceed 5 ÷ 7%.

The proposed and described methodology of the diesel locomotive exploitation load cycle dynamic indicator reduction, by the use of which the following is achieved: increase of the diesel work duration by 7÷10%, reduction of fuel consumption up to 10%, reduction of the load cycle dynamic indicators (increasing the fatigue stress of parts and units of the diesel) by 15÷20%.

ИССЛЕДОВАНИЕ ВЛИЯНИЯ НАГРУЗКИ НА ДОЛГОВЕЧНОСТЬ ДВИГАТЕЛЕЙ ГРУЗОВЫХ ЛОКОМОТИВОВ

Аннотация. Статья отражает результаты исследований, связанных с рационализацией подвижного состава ОАО Литовские железные дороги для улучшения показателей надежности эксплуатации грузовых тепловозов. Сравнительная оценка длительности эксплуатационной работы грузового тепловоза в соответствии с технической документацией базируется на результатах сравнительных испытаний и косвенных критериев надежности дизелей, полученных в практике. Был предложен алгоритм прогнозирования продолжительности эксплуатационной работы, а также программный комплекс для математического моделирования. Различие результатов, полученных экспериментально и моделируемых с помощью компьютера, не превышает 5 ÷ 7%.

Предложены и описаны методология снижения динамического индикатора эксплуатационного цикла нагрузки тепловоза, с помощью которого достигается следующее: увеличение продолжительности работы дизеля на 7 ÷ 10%, снижение расхода топлива до 10%, снижение динамических показателей цикла нагрузки (снижение усталостных напряжений деталей и узлов дизеля) 15 ÷ 20%.

1. INTRODUCTION

In the latter decade the situation of the railway transport has dramatically changed in Europe. The potential of the railway transport is being created in a systematic and rapid way, which is oriented to the increasing dependence of the modern economy on transport, taking into consideration the dynamics of the demand, the variety of the ownership, the flexibility of servicing and the needs of technique and technology. As Lithuania acceded the European Union, the reconstruction of the Lithuanian railways and their integration into the transport system of the European railways became one of the priority objectives of the *government of the Republic of Lithuania*. In particular, for the creation of new services and encouraging intermodality, in the traction rolling stock fleet of JSC "Lietuvos geležinkeliai", in the recent five years huge transformations have been taking place. JSC "Lietuvos geležinkeliai" has become the first company in the Baltic region, which started a complex and responsible diesel locomotive modernization programme, which ensures for Lithuanian railways a vital traction rolling stock renewal programme. These changes of the fleet allowed increasing the effectiveness of the consumption of energy resources and improving the ecology indicators of exploitation. The strategic objective of the complex research carried out has become to research, to formulate and to substantiate the possible reserves of improving the exploitation reliability, energy and ecology indicator improvement of the main diesel locomotive fleet exploitation, the directions and their realization measures ensuring more effective functioning of the transport of the Lithuanian railways. The main emphasis in the research of this publication has been put on the reliability indicators of the diesel locomotive diesels.

2. METHODS AND CRITERIA FOR FORECASTING OF DIESEL ENGINE OPERATING TIME

To determine the reliability of diesel locomotives operating parameters and to forecast their operating time, the similarity theory and computer simulation methods are applied. The criteria of thermal and mechanical load of components approved in practice, describing the features and operational process characteristics of the diesel, are used.

During the operation of diesel engines of similar series in the same type of locomotives, depreciation of units and components can be significantly different. This is explained by wide operating mode spectrum of diesel engines. It depends on the profile of the drive of locomotive (electric, hydraulic or mechanical drive), destination (trunk, passenger or shunting locomotive) road (uphill or plain, curve or straight line). Intensity of component depreciation is defined by friction rate of surface movements in respect of each other, the values of the pressure of agents and the temperature of friction surfaces. It is impossible to analyse all of these indicators in detail and reliably, so the criteria [1], which examine the flow of heat, its offtake to the cylinder heads and sleeve walls or the surfaces of the components of some cylinder - piston group and their temperatures.

Basically, the following criteria may be perceived as the diesel reliability criteria, because the latter indirectly, but complexly reflect the design of diesel engine, perfection of production technology and features of operating conditions.

Principled possibility of application of such criteria is based on the change of similar temperatures in the components of various types and a high-speed engine cylinder - piston group (depending on the load, on the revolutions of crankshaft and inflation air pressure). After completion of exploratory tests of depreciation of the components of cylinder - piston group [2] and processing of the results obtained, main indicators of the engine, the most influencing growth rates of the depreciation of cylinder - piston group, were determined. This is average effective pressure P_{me}, maximum cycle pressure $P_{\max}$, excess air ratio α, exhaust gas temperature T_T, average piston speed C_m, inflation air pressure P_K and revolutions of crankshaft speed n. Change in these parameters is anyway associated with the changes in temperatures of the components of cylinder - piston group and temperature stress by almost linear dependences.

One of the first complex criteria for indirect piston thermal strain was proposed by Prof. *B.J. Ginsburg* [1]:

$$P_D = \frac{P_e}{i \cdot D}, \quad \text{kW/cm}; \tag{1}$$

where: P_e – nominal motor power, kW; D – diameter of cylinder, cm; i – number of cylinders.

Critical value of criterion P_D, where the temperature of the piston will reach marginal values, depends on the type of diesel engine.

More complicated complex indirect criterion was presented by Prof. *A.K. Kostin*. He proposed to use the following expression for indirect assessment of piston thermal stress and determination of medium thermal flow over the cooled cylinder surfaces:

$$\xi = P_{\max} \cdot \left(\frac{1}{\alpha}\right)^{0,88} \cdot \left(P_K \cdot C_m\right)^{0,5} \cdot n; \tag{2}$$

where: C_m – average piston rate, m/s; α – air excess ratio; P_K – air inflation pressure, MPa; $P_{\max}$ – maximum cycle pressure, MPa; n – revolutions of crankshaft, rev./min.

This criterion has become a very popular in design and exploratory practice. Based on this in dimensional parameter, it was possible to optimize the values of inflation parameters. The criterion ξ is directly related to the temperatures of piston, cylinder head and cylinder sleeve.

Other complex indirect thermal stress criteria may also be used (of "Ricardo" company, Prof. S.V. Kamkin's *"CNIDI"*, Prof. M.I. Fedorov et al. [1]). However, these are complicated criteria of complex indirect thermal stress where the parameters received during engine bench tests are required for their setting.

3. ASSESSMENT OF RELIABILITY OF DIESEL ENGINES OF LOCOMOTIVES ACCORDING TO OPERATING TIMES

Studies were carried out in the locomotives' park of AB „Lietuvos geležinkeliai" (AB "Lithuanian Railways"). Below the data of locomotives and their engine manufacturers on operating ranges used for studies are shown.

1. Diesel engines *of "Kolomna Energy Service OU*" company (Russia):
   - Life of *engine 14D40* (locomotives *M62* and *2M62*) - *8.640.000 l* burned fuel [1]**;**
   - Life of *engine 2 – 2D49* (locomotives *M62K* and *M62K*) - *1.500.000 km run or 12 y.* [4];
   - Life of *engine 11D45* (locomotive series *TEP 60*) - *4.104.000 l* burned fuel [1]**;**
   - Life of *engines 2A – 5D49 and 2A – 5D49 – 01* (locomotive series *TEP 70 and TEP 70 BS) – 1.250.000 km run* [6];
2. Life of *CAT 3512B HD - SC* series diesel engines *of* "*Zeppelin – Cat Power Systems*" corporation (Germany – the USA) (locomotives *2M62M and 2M62UM*) - *5.840.000 l* burned fuel [3];
3. Life of *MTU 16V 4000 R41* series diesel engines *of* "*MTU Friedrichshafen GmbH* " company (Germany) (locomotives *ER 20 CF*) - *48.000 mh or 18 y.* [5].

It is appropriate to express the operating time given by the manufacturers in years (based on statistic relative averages set by *AB "Lietuvos geležinkeliai*" during the operation [7, 8]):

1. *M62* and *2M62* series locomotives with *14D40*-type diesel engines are the most widely examined of all the mentioned types of locomotives. According to operating parameters of the statistical averages [8, 9] of *AB "Lietuvos geležinkeliai"*, one diesel engine of the locomotive burns 1.5 million litres of fuel per *15.000 mh*. Therefore, the overhaul time of one *M62* or *2M62* locomotive equals *8640 mh*. Average daily operating time of diesel locomotive is *16 hours*. Assuming that the locomotive operates all year round, *365* days by *16 hours*, after doing arithmetic actions (86400 / 365·16 = 14.8 *y*), we get that the average time life of diesel engines of *M62* and *2M62* locomotives before overhaul equals *14.8 years*.
2. Re-motorized *M62K* and 2M62K type locomotives are equipped with *2 - 2D49* series diesel engines. According to manufacturers [4], the resource before the overhaul equals *1.500.000 km* of locomotive run or *12 years* of operation. Having divided the number of run kilometres by

the number of operation years, we get that average annual run is *125.000 km*. This value is close to statistical average value of run operation of *AB* “*Lietuvos geležinkeliai*“ locomotives – *100.000 km per year* [8]. The statistical value was used during the analysis of stock aging control in 2003 [63]. After the recalculation of the run of 125.000 km/year to 112500 km/year, 13.5 years or 78840 mh operating time was received.

3. *TEP 60, TEP 70 and TEP 70BS* are passenger trunk locomotives. Operating load cycle of those diesel locomotives is basically different from the diesel engines of trunk freight locomotive. Therefore, it is appropriate to predict operating time of this group of diesel locomotives using indirect criteria separately.
4. Modernized *2M62M and 2M62UM* locomotives with CAT 3512B HD - SC series diesel engines of “Zeppelin - Cat Power Systems” corporation are assessed similarly, like the *M62*. According to manufacturers, their life before overhaul is *5.840.000 l* of burned diesel fuel. This makes 12.4 years or 59400 mh.
5. For new *ER 20 CF*-type locomotives of *“MTU Friedrichshafen GmbH”* company with *MTU 16V* 4000 *R41*series diesel engine, the manufacturers declare the life *of 48.000 mh* or 18 years of operation before the overhaul. 18 years operation is only possible if the condition of manufacturers [11, 12] that diesel engines will work according to the standard *ISO 8178-4, F* load cycle is followed. Moreover, having calculated the average daily operating range of locomotive, the proportion *48.000 mh/18 y* will be kept only if the diesel engine of locomotive runs at least *7 hours* a day. Average daily operating time of *AB* “*Lietuvos geležinkeliai*“ a trunk locomotive is *16 hours* (double than provided by manufacturers). Due to an increase in the average operating time, the run of locomotives increases as well as the amount of burned fuel, respectively; therefore, the life before the overhaul period should be shortened. Recalculation showed that the life is shortened from 18 years up to *8.2 years*.

All average values of time life of diesel engines before the overhaul and indirect thermal stress criteria analyzed previously are presented in Table 1.

Table 1

Indirect criteria for assessment of AB “LG“ the reliability of trunk cargo diesel locomotives

Company manufacturer	Diesel engine series	Locomotive series	B. J. Ginsburg criterion	A. K. Kostin criterion	Operating time, mh
„Kolomna Energy Service OU“	*14D40*	*M62–2M62*	*1,0**	*1,0**	*86400*
	2 – 2D49	*M62K–2M62K*	*0,89*	*1,22*	*78840*
„Zeppelin – Cat Power Systems“	*CAT 3512B HD – SC*	*2M62M 2M62UM*	*1,26*	*4,52*	*59400*
„MTU Friedrichshafen GmbH“	*MTU 16V 4000 R41*	*ER 20 CF*	*1,44*	*5,08*	*48000*

Note: ** – generally, Ginsburg and Kostin criteria for 14D40 engines are equal to 1, and for other engines they are calculated according to the ratio.*

For the approval of criteria, the correlation reliance between comparative cargo locomotive diesel operating time before the overhaul (T) and indirect A.K. Kostin criterion ξ is given at the study objects in Fig. 1. The value 0.96 of the determination coefficient R^2 shows strong reliance between T and ξ.

However, during the assessment of the link between the selected criteria and operating time of locomotive engines, the structure of operating cycle must be taken into account. ISO 8178-4 (F) standard indicates that operating cycle of locomotive diesel consists of three main modes: nominal power, 50% of the load and idle run. Criteria have been approved using the actual structure of operating (pilot) load cycle of locomotive diesel (see Table 2).

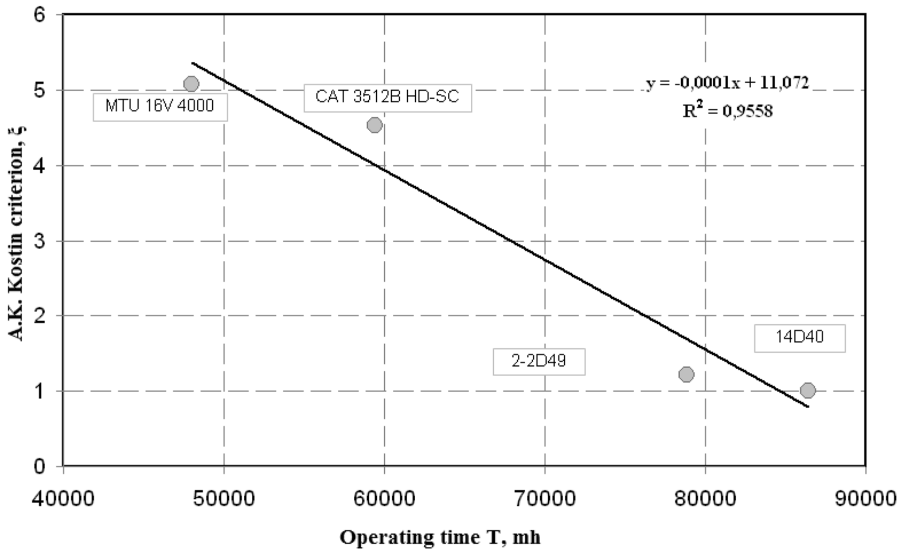

Fig. 1. Inter-reliance of operating time (T) of AB “LG” cargo locomotives and indirect criterion ξ
Рис. 1. Внутренняя зависимость рабочего времени (T) AB “LG” грузового локомотива и косвенного критерия ξ

Table 2

Operating load cycle of locomotive diesel according to ISO 8178-4(F)

Power (load)%	100 %	50 %	Idle run
Revolutions, %		intermediate	
Relative part of operating time	0,25	0,15	0,60

The value of the criteria for nominal power, 50% of the load and idle run modes are calculated. Having assessed the structure of operating cycle of engines, the results of calculation of reliability criteria are presented in Table 3.

Table 3

Values of AB “LG“ cargo locomotive diesel reliability criteria calculated in accordance with the operational test cycle modes (ISO 8178/4)

	P_d	ζ	$q_П$	Load
MTU16V4000R41	10,1	32230	1,133	100 %
	5,06	11980	0,815	50 %
	0,606	655	0,214	Idle run
	3,65	10245	0,533	Mean values of cycle
Caterpillar 3512B HD-SC	8,33	24738	1,004	100 %
	4,1	8300	0,78	50 %
	0,49	548	0,203	Idle run
	2,81	7758	0,489	Mean values of cycle
2-2D49	4,712	6878	0,69	100 %
	2,35	2805	0,594	50 %
	0,484	308	0,193	Idle run
	1,82	2325	0,377	Mean values of cycle
14D40	2,663	4965	0,602	100 %
	1,34	1890	0,427	50 %
	0,274	484	0,242	Idle run
	1,31*	1815	0,360	Mean values of cycle

*) A multiplier 0.5 is introduced in the formula of Prof. Ginsburg’s value criterion P_d applicable to double-stroke 14D40 diesel compared with a four-stroke diesel.

Mathematical relationship between the reliability criteria of engines and the resource is shown in Fig. 2, 3 and 4.

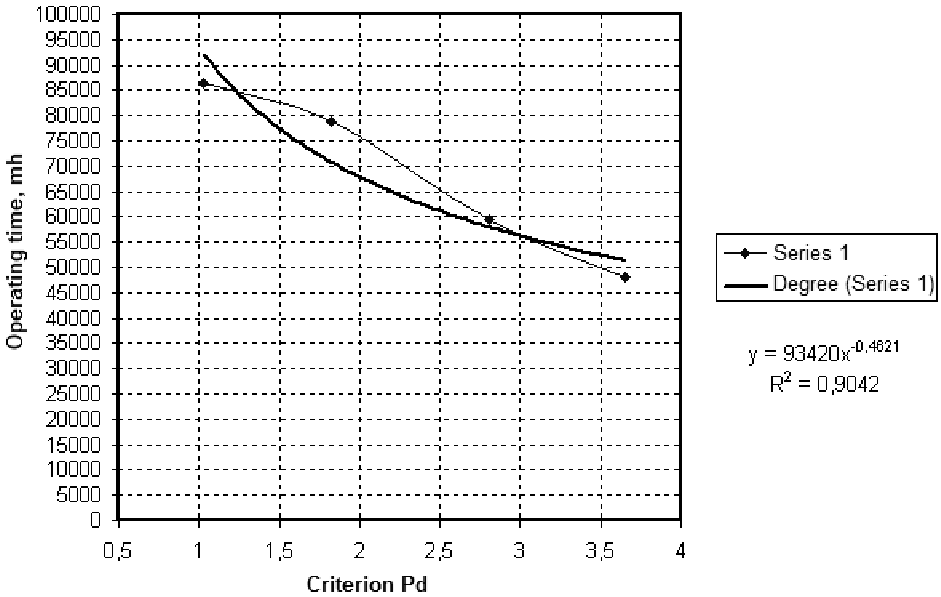

Fig. 2. Results of P_d criterion adaptation to AB "LG" cargo locomotive diesels
Рис. 2. Результаты P_d критериальной адаптации для дизелей AB "LG" грузовых локомотивов

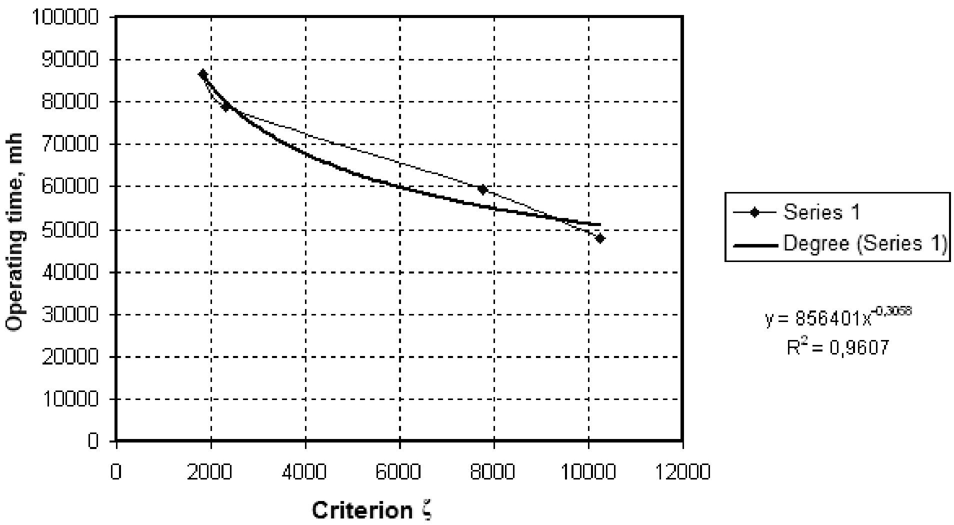

Fig. 3. Results of ζ criterion adaptation to AB "LG" cargo locomotive diesels
Рис. 3. Результаты ζ критериальной адаптации для дизелей AB "LG" грузовых локомотивов

High coefficients of determination R^2=0.91÷0.98 show the adequacy of application of the criteria examined in further studies.

4. INCREASING DIESEL LOCOMOTIVE EXPLOITATION EFFECTIVENESS INDICATORS BY CHANGING THE PARAMETERS OF THE LOAD CYCLE

Creating traffic schedules for 1520 mm track, the railway system adopted the principle of shortest travel time. The train had to reach allowable speed as soon as possible. The following traffic scheduling principle is still used in many places now. It is also applied in Lithuania. The principle of traction restriction was applied during the study. Actual maximum traction power was limited to 0.83 and 0.67 of the maximum possible power, respectively. Two major transit corridors go through Lithuania: Kena-Klaipėda and Kena - Kybartai. The first one is a corridor to the Lithuanian port of Klaipeda, and the second is the corridor to the Russian port of Kaliningrad. Section Kena-Kybartai was used for studies. Traction restriction indicators of 2M62M locomotive on track Vaidotai-Kybartai related to diesel energy and reliability indicators are presented in Table 4.

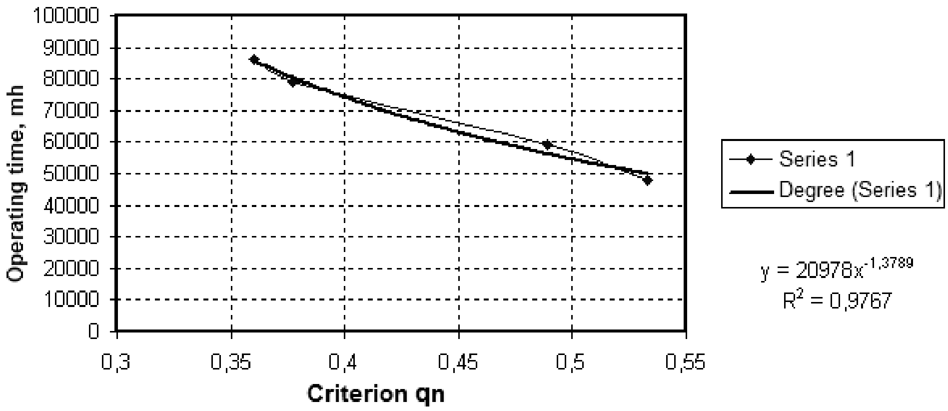

Fig. 4. Results of q_n criterion adaptation to AB "LG" cargo locomotive diesels
Рис. 4. Результаты q_n критериальной адаптации для дизелей AB "LG" грузовых локомотивов

Table 4

Influence of traction restriction for 2M62M locomotive on track Vaidotai-Kybartai on diesel energy and reliability indicators

Train mass, t	Traction restriction coefficient	P_{evid}, kW	P_e maximum short-term value, kW	P_e maximum long-term value, kW	Load spectrum structure	Gf_{vid}, kg/h	b_{evid}, g/kWh	ΔK_2, %	T_L, min.	V_{vid}, km/h
4000	1	775	1600	1200	Fig. 5	159	210,5	1,1	171	64,6
4000	0,83	754	1350	1150-1200	Fig. 6	155	210	-0,2	177,1	62,4
4000	0,67	754	1300	1200-1250	Fig. 7	154,5	210	-0,2	186,4	59,2

As the traction in the diesel locomotive line 2M62M Vaidotai-Kybartai was reduced by 34%, the main diesel locomotive exploitation indicators have practically remained the same, and the trip duration increased to 15.4 min (once the speed was reduced from 64.6 km/h to 59.2 km/h). However, in parallel to this, the load spectrum amplitude is significantly reduced too (the place chosen for the analysis is the line section 120-140 km, see Fig. 5, 6, 7). The power change frequency has been reduced, and the load spectrum was moved to the average power area, by simultaneously reducing the nominal power of the work duration and also in idle regimes. A more significant positive effect is received by limiting the traction characteristics of the traction diesel locomotive 2ER20CF (e.g. in line Bugieniai-Klaipėda, Draugystė with the train set mass of 4800 t). The power change amplitude is significantly reduced: from 2000 kW to 1400–1500 kW, the power frequency is reduced approximately twice. The power change amplitude was reduced from 1880 kW to 1280 kW, i.e. 32%, and the short-term P_e increase completely disappeared.

M62M locomotive load cycles at different load restrictions are shown in Figures 5, 6 and 7.

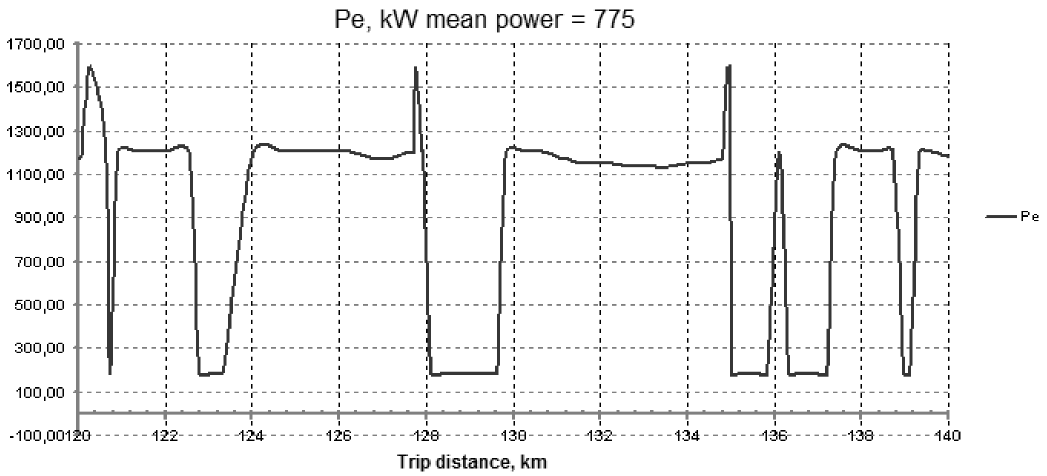

Fig. 5. 2M62M locomotive load cycle parameters on track Vaidotai-Kybartai (without traction restriction)
Рис. 5. Параметры цикла нагрузки локомотива 2M62M на участке Vaidotai-Kybartai (без ограничений по тяге)

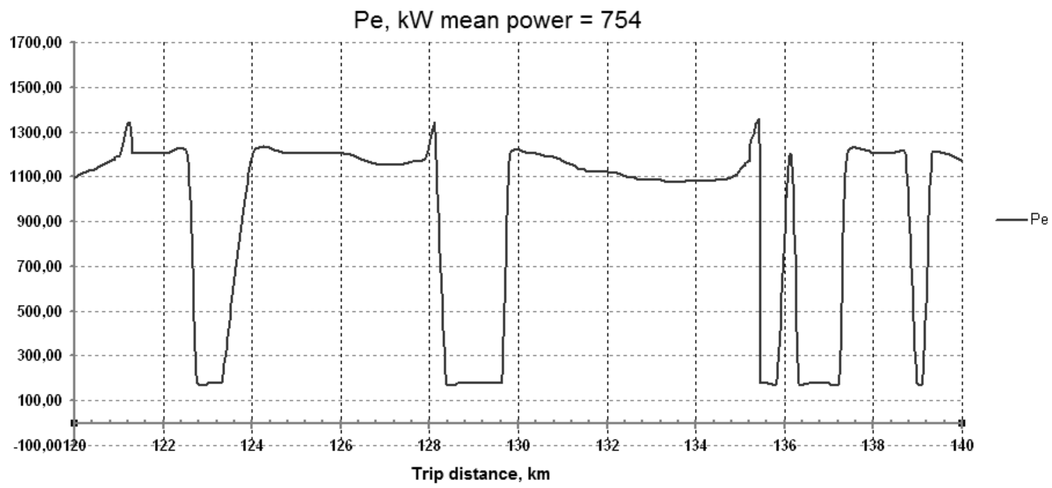

Fig. 6. 2M62M locomotive load cycle parameters on track Vaidotai-Kybartai (traction restriction coefficient 0.83)
Рис. 6. Параметры цикла нагрузки локомотива 2M62M на участке Vaidotai-Kybartai (коэффициент ограничения по тяге 0.83)

According to the aforementioned methodology, maximum masses of the train set are established according to the foreseen diesel locomotive work duration reduction (R_2) by not more than 10%, as compared to the declared work durations of the producing company. To increase the adequacy of the establishment criteria of the maximum train set mass, the changes of the ζ criterion are used $\Delta\zeta(\Delta K_2)$.

Section Vaidotai-Kybartai consists of two different sections according to the load of locomotive diesels: Kena-Vaidotai and Vaidotai-Kybartai. On the first section the average diesel load is less and makes 32.5% of the nominal power of diesel P_{enom}, and on section Vaidotai-Kybartai average diesel load of locomotive reaches 50-60% P_{enom}. Therefore, the result of engine power restriction is different. Figure 8 shows how the change of locomotive engine life R_2 depends on the train mass on sections Kena-Vaidotai and Vaidotai-Kybartai. On the first section (when average engine load is 32.5% of the nominal power) the increase by 20% of the life is notable. Where as on the second section (when average engine load is 50-60%), a fore mentioned corrections can even reduce the engine life. Of course, the change of life depends on the train mass. This is natural, because the actual load of the engine is determined by the train mass. Also, the change of life is a bit different for different locomotives.

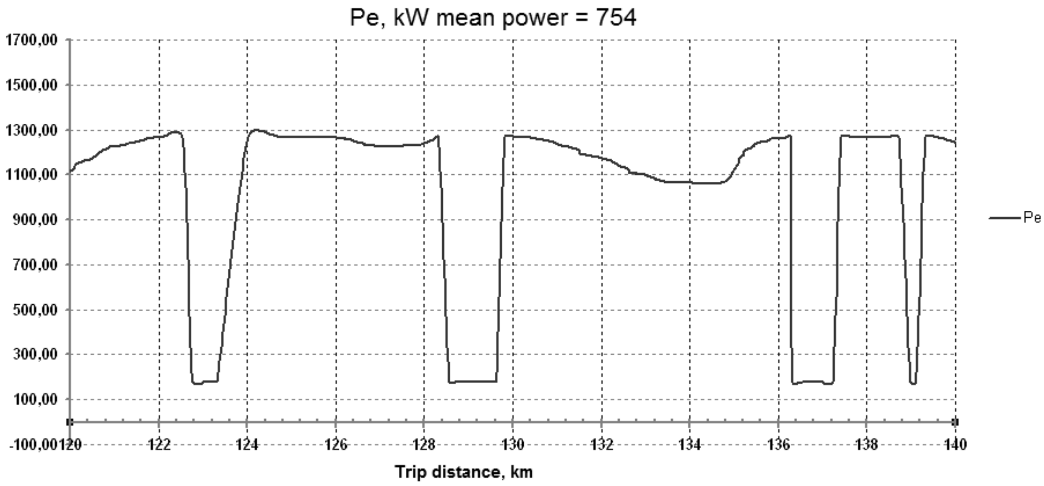

Fig. 7. 2M62M locomotive load cycle parameters on track Vaidotai-Kybartai (traction restriction coefficient 0.67)

Рис. 7. Параметры цикла нагрузки локомотива 2М62М на участке Vaidotai-Kybartai (коэффициент ограничения по тяге 0.67)

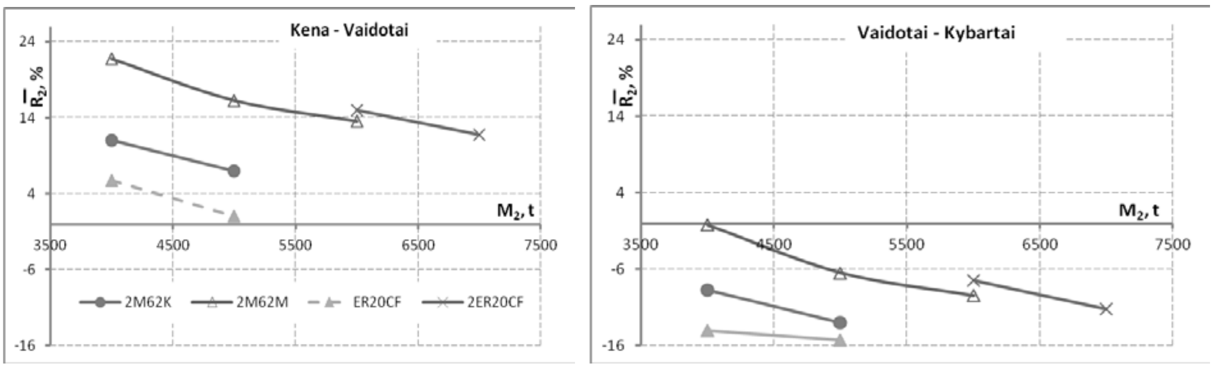

Fig. 8. Predicted R_2 relative change in operating time of locomotive diesels on section Kena-Vaidotai-Kybartai

Рис. 8. Предсказанные относительные изменения R_2 по времени эксплуатации дизелей локомотивов на участке Kena-Vaidotai-Kybartai

Summarizing the consistent patterns shown in Figure 8 and provided information, it is evident that restricting maximum engine power of the locomotive, engine life can be increased when the average engine load at the end of load cycle is about 30% of nominal power after the restriction.

5. CONCLUSIONS

1. According to statistic data, it was proved that using the criteria of *A.K. Kostin* and *B.J. Ginsburg*, the life of locomotive diesel engines can be predicted: the life declared by different (independent) engine manufacturers correlates well with the criteria calculated according to the data of their engines, respectively.

2. Both mathematical simulation and field studies confirm that the engine life can be increased through restriction of maximum power of locomotive engine, and the increase in life can be by 10-15% on the average.
   Restricting maximum engine power of the locomotive, engine resource can be increased when the average engine load at the end of load cycle is about 30% of nominal power after the restriction.
   When real average power is greater than that provided in a standard cycle during the operation, the operating time of locomotive engines may be less than that declared by the manufacturers.
3. The proposed methodology of the diesel locomotive exploitation load cycle dynamic indicators reduction (causing worsening of the reliability, energy and ecology diesel characteristics), which is meant for practical use by using freight diesel locomotives and by planning JSC “LG” freight transportation and by compiling schedules.
   The analysis of the methodology created and its approval by a calculation experiment confirms the rationality of its use by transporting JSC “LG” freights:
   - The increase of the work duration of the diesel locomotives is 7–10%;
   - The reduction of the load cycle dynamics indicators (P_e maximum amplitude) accounts for 15 – 20%;
   - The duration of the trip increases not more than by 20–30 min in 200–230 km length lines.

   Established rationals according to the diesel reliability criteria in the train set mass in the main lines of JSC “LG” railway network freight transportation.
4. By using the created programme complex, a large calculation experiment has been carried out, on the basis of which rational train set masses are established according to the diesel reliability criteria in all major freight transportation lines of the JSC “LG” railway network.

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