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## EVALUATION OF THE OPERATIONAL RELIABILITY AND FORECASTING OF THE OPERATING LIFE OF THE POWER TRAIN OF THE FREIGHT DIESEL LOCOMOTIVE FLEET

### OCENA NIEZAWODNOŚCI EKSPLOATACYJNEJ I PROGNOZOWANIE ŻYWOTNOŚCI UKŁADU PRZENIESIENIA NAPĘDU WE FLOCIE SPALINOWYCH LOKOMOTYW TOWAROWYCH

*The article provides analysis of the passivity of various options for the rational use of the fleet of diesel locomotives with the purpose of improving the operational reliability indicators of diesel engines installed on freight diesel locomotives. The rationality of the use of mathematical statistical methods, with their application to in-service diesel engines installed on diesel locomotives, was assessed with the use of the accumulated statistical data on breakdowns/disorders of main-line diesel locomotives of State Company "Lietuvos geležinkeliai" (Lithuanian Railways). On the basis of technical documentation, with the use of the results of comparative tests and practically approbated indirect diesel engine reliability criteria, the comparative assessment of the operating life of in-service diesel engines installed on freight diesel locomotives has been performed. In order to substantiate the adequacy of tests, the adaptation of the programme modules of mathematical computer simulation of the parameters of diesel engines of the fleet operated by Lithuanian Railways. The differences between the results established by the experiment and simulated by the computer do not exceed 5–7 %. The indirect criteria of evaluating the mechanical and thermal load of parts of diesel engines installed on diesel locomotives have been selected and adapted. An algorithm of the methodology for the evaluation of the reliability criteria of diesel engines installed on diesel locomotives and forecasting of the operating life has been developed. It has been implemented in the form of a mathematical simulation programming complex.*

**Keywords:** diesel engine of locomotive, indirect reliability criteria, operating life.

*Artykuł przedstawia analizę pasywności różnych opcji racjonalnego wykorzystania floty lokomotyw spalinowych mającą na celu poprawę wskaźników niezawodności eksploatacyjnej silników wysokoprężnych użytkowanych w towarowych lokomotywach spalinowych. Zasadność stosowania matematycznych metod statystycznych do analizy eksploatacji silników wysokoprężnych użytkowanych w lokomotywach spalinowych oceniano z wykorzystaniem zgromadzonych danych statystycznych dotyczących awarii / nieprawidłowego działania lokomotyw spalinowych jeżdżących na głównych liniach kolejowych Firmy Państwowej „Lietuvos geležinkeliai” (Koleje Litewskie). Na podstawie dokumentacji technicznej, z wykorzystaniem wyników testów porównawczych i sprawdzonych w praktyce pośrednich kryteriów niezawodności silników wysokoprężnych, dokonano oceny porównawczej żywotności silników wysokoprężnych zamontowanych w towarowych lokomotywach spalinowych. W celu potwierdzenia trafności badań, zastosowano moduły programowe matematycznej symulacji komputerowej parametrów silników wysokoprężnych floty eksploatowanej przez Koleje Litewskie. Różnice pomiędzy wynikami otrzymanymi na drodze doświadczalnej a wynikami symulowanymi komputerowo nie były większe niż 5–7%. Wybrano i przyjęto pośrednie kryteria oceny mechanicznych i termicznych obciążeń części silników wysokoprężnych zamontowanych w lokomotywach spalinowych. Opracowano algorytm metodyki oceny kryteriów niezawodności silników wysokoprężnych użytkowanych w lokomotywach spalinowych oraz prognozowania ich żywotności. Został on wdrożony w postaci kompleksu do programowania symulacji matematycznych.*

**Słowa kluczowe:** silnik wysokoprężny lokomotywy, pośrednie kryteria niezawodności, żywotność.

#### 1. Introduction

In the last decade, Europe is forced to resolve unprecedented problems raised by transportation: traffic flows have increased significantly, and the leading role has been taken by road transport, which appeared to be better adapted to new economic phenomena. The domination of this mode of transport in Europe poses serious problems (traffic congestions, hazardous impact on the environment and human health, and threatening statistics of traffic accidents).

In order to mitigate these problems, the European Council and the European Commission have taken the following actions: increase of taxes on road transport, renewal of alternative means of transport (encourage-

ment of the use of seaborne and inland waterway transport, revitalisation of railways, and development of multimodal transport operations).

In their turn, international railway organisations, such as the International Union of Railways (UIC), the Community of European Railways (CER), the International Union of Public Transport, (UITP), and the Union of European Railway Industries (UNIFE) agreed to increase during the period 2000–2020 the market share to be taken by railways from 6 % to 10 %, and that in the area of freight transportation from 8 % to 15 % as well as to decrease the emission of pollutions by 50 %.

During the last decade, the situation in railway transport in Europe changed in principle. The potential oriented to the growing dependency of the economy on transport, with regard to the dynamics of de-

mand, variety of ownership, service flexibility, and needs of engineering and technology has been created in a systemic and rapid manner. This process has been influenced by qualitative changes introduced by laying fast communication railways and constructing new rolling stock. Railway transport has become competitive owing to high speed, comfort, high service level, traffic safety and environmental friendliness.

Today the railway transport sector is assessed as an especially important segment of economy, which to a great extent determines the movement of goods within the country and their transportation abroad, which has a significant impact on all companies of the country – consignors and consignees as well as related businesses.

It is the establishment of new services and promotion of intermodality which was the purpose of the great changes that took place in the fleet of rolling stock of Lithuanian Railways during the recent five years. According to the requirements set by Directive 2001/12EB of the Parliament and the Council to reform the rolling stock system by separating operational activities from rolling stock repair works, company “Vilniaus Lokomotyvų Remonto Depas” was established in 2003. It was this subsidiary of Lithuanian Railways to which the main goal was set: to restore the existing fleet of traction rolling stock, to find methods to modernise diesel locomotives and to implement the requirements set by the Directive. Therefore, this company became the first in the Baltic region which started a programme for complex and responsible modernisation of rolling stock. Besides, in 2005 the unprecedented agreement of Lithuanian Railways with Siemens AG (Germany) was signed, according to which 34 units of customised ER 20CF series diesel locomotives were to be manufactured.

These changes allowed enhancing the efficiency of the consumption of resources and improving the operational environmental indicators. Both these aspects perfectly meet the requirements specified in the Directive of the Parliament and the Council concerning the control and improvement of energy resources consumption efficiency (COM (2001) 370).

With fleets of diesel locomotives being constantly supplemented with new and modernised traction units, it became a strategic goal of complex studies to investigate, form, and substantiate possible reserves and directions of the improvement of operational reliability as well as energy and environmental indicators and measures for their implementation ensuring more effective functioning of the Lithuanian Railways transport because the reliability of diesel engines determines to a great extent determines not only economic, but also environmental operational indicators of diesel locomotives. This is why this article describes the main accent of the studies performed, which is devoted to the reliability indicators of diesel engines of diesel locomotives.

## 2. Assessment of the operational reliability of a diesel engine determined by methods of mathematic statistics

The factors characterising the reliability of a diesel engine of a diesel locomotive are divided into structural, technological, and operational.

Analysis of the operation of diesel engines [1–6, 14, 15] shows that breakdowns during their operation occur as a result of infringement of the technical maintenance and repair regulations, improper use of the operational materials regulated in the technical documentation, and long-term operation under overloaded modes.

Referring to the aforementioned, it can be claimed that it would be reasonable to envisage in comparative studies of the operational reliability indicators of diesel engines of different types installed in diesel locomotives, first of all, analysis and comparison of their reliability indicators with regard to environmental and operating conditions.

Practice shows that the main criterion of the enhancement of the durability is the improvement of the resistance of reliability limit-

ing assemblies and parts (the cylinder-piston group, crank-piston rod mechanism, assemblies of inflation and fuel injection systems, etc.) to wear.

Depending on the operating time of the diesel engine, the indicators representing its reliability (breakdown intensity, density distribution  $f(t)$ , and probability distribution  $P(t)$ ) are described by the different laws of mathematical statistics described below:

1. For newly commissioned diesel engines, for which breakdowns of technological (production) character are inherent during the running-in (assembling, metal processing, etc.), the logarithm density distribution is applied, which is expressed by the following formula:

$$f(t) = \frac{1}{t\sigma\sqrt{2\pi}} \exp\left(-(\ln t - a)/2\sigma^2\right), \quad (1)$$

where:  $\sigma$  – standard deviation;  $t$  – exploitation duration till failure;  $a$  –  $\ln t$  average value.

2. For new diesel engines that have passed the running-in period and are at the beginning of the normal operation period, the characteristic exponential probability distribution law; breakdowns mostly have the character of sudden occurrence as a result of local thermal or mechanical overload of parts, infringement of operating rules, etc. The law of characteristic exponential probability distribution is expressed by the following formula:

$$P(t) = l \frac{t}{T}. \quad (2)$$

where:  $T$  – average working duration without failure;  $l$  – fixed interval of duration;  $t$  – exploitation duration till failure.

3. For objects that have been in operation for a long period of time (when the operating  $l$  approaches the life limit), the processes of part wear and metal aging accelerate; correspondingly, the flow of breakdowns grows intensively and is described in the best manner by the normal probability distribution law:

$$P(t) = 1 - \frac{1}{\sigma\sqrt{2\pi}} \cdot l \cdot \frac{-(t_i - \bar{T})^2}{2\sigma^2} \quad (3)$$

where  $\sigma$  – standard deviation;  $T$  – average working duration without failure;  $l$  – fixed interval of duration;  $t_i$  – working time till failure of  $i$ -th element.

In order to apply one or the other of the aforementioned laws for the establishment of reliability, a certain number of tests (breakdowns), which requires a long period of time under natural operating conditions, is necessary. Collected statistical data according to corresponding locomotive types range from 4 to 12 years of operating period.

From the available collected data, especially for new locomotives, this number is so far insufficient in order to apply the aforementioned probability laws directly. In such cases, Student's coefficient is applied, which is chosen depending on the numbers of tests and the degree of the selected probability.

On the basis of the review and analysis of the mathematical statistics methods, when applying them to study objects, the following is stated:

- 1) for the determination and forecasting of the reliability indicators of diesel engines, quite a comprehensive array of statisti-

cal data on their breakdowns is necessary: in the case of normal law (distribution probability  $\beta = 0,9-0,95$ ; variation factor  $n_v = 0,20$ ), the number of the elements of diesel engines under the study (differentials according to characteristic groups of parts: the cylinder-piston group, crank-piston rod mechanism, assemblies of inflation and fuel injection systems, etc.) should be at least 40–60 items; in the case of applying the Weibull law – 50–60 items and more ( $\beta = 0,95$ ; relative error 5–10 %);

- 2) with the application of mathematical statistics methods for studying the reliability indicators of diesel engines installed on diesel locomotives of Lithuanian Railways, attention must be paid to the following:
  - obsolete and newly modernised diesel engines installed on diesel locomotives are in different stages of the operating cycle (normal operation; intensive aging); methodologically, they should be subject to different probability distribution laws and, when comparing calculation results, it should be taken into account [7, 9];
  - data on breakdowns of new/modernised diesel engines, as we mentioned above, are not sufficient; therefore, the Student's adjustment shall apply here.

Upon evaluation of the entire versatility of statistical data, during short operating period (for new locomotives), computer simulation and similarity theory methods were applied in this study for the establishment of the reliability of operating parameters of diesel engines installed on diesel locomotives and forecasting of operating duration, i.e. with the use of the practically proved criteria of the thermal and mechanical load of parts which define the structural and operating process peculiarities of diesel engines [9, 11, 13, 14].

The ongoing energy-mass transfer within the subsystems of the third level is driven by gradients of temperature, stress, chemical potentials and dislocation density. The direction of the energy-mass transfer is opposite to the vector of gradient of chemical potential, so the decrease in its intensity occurs in the course of the development of the process.

### 3. Selection of indirect criteria for the forecasting of the operating life of a diesel engine

When operating diesel engines of the same series installed on diesel locomotives of the same type, the degree of wear of assemblies and parts may differ remarkably in regard to separate models. This fact is substantiated by a wide spectrum of possible operating modes of diesel engines, which is highly dependent on the relation of the engine with wheel-sets (electrical, hydraulic, and mechanical drive), its intended purpose (main-line, passenger, and shunting transport), and track profile (slopes and turns), etc.

On these grounds, in practice, of relevance is the evaluation of the degree of wear of the cylinder-piston group (CPG) and parts of the slider-crank mechanism (as more limiting the reliability of the diesel engine and life of the assemblies). According to it, both the direct and inverse task can be resolved: the determination of the rational inter-maintenance period and residual life of the engine under a certain degree of diesel engine load when carrying freights (direct task); optimisation of the operating load cycle parameters at lines in order to extend the duration of operation (transport operations) inverse task.

The wear rate of parts under equal conditions (equal design arrangements of engines, manufacturing technologies and materials, types of fuel, and lubricants) are basically defined by the movement speeds of friction surfaces in respect of each other that are exposed to pressure forces and temperature values of friction surfaces. Since the proper evaluation of the thermal condition of parts and assemblies and mechanical load under operating conditions is difficult to implement due to technical and design constraints, various methods and criteria [8], which either reflected the thermal flow directed to walls of cylinder

heads and hubs, or temperatures of certain parts of the cylinder-piston group which, in their turn, define the indirect criteria of thermal and mechanical stresses of those parts or the whole engine, started to be proposed [7].

The fact that priority in similar studies is given to the analysis of thermal stresses is substantiated by the statistics of experimental and calculation data. Thermal stresses of CPG parts account for 80–90 % of the aggregate balance of thermal and mechanical stresses [13].

The principal possibility of the application of such criteria is substantiated by temperature changes of similar character in parts of the cylinder-piston group in engines of various types and rapidity depending on the load, rotations of the crankshaft and inflation air pressure.

The performance of research tests of the wear of parts of the cylinder-piston group and processing of the results obtained during those tests allowed determining the main operating indicators of engines that influence the rate of growth of the wear of the cylinder-piston group most of all: mean effective pressure  $P_{me}$ , maximum cycle pressure  $P_{max}$ , excess air ratio  $\alpha$ , exhaust gas temperature  $T_T$ , average piston speed  $C_m$ , inflation air pressure  $P_K$ , and crankshaft rotations  $n$ . Increase in these parameters is in one way or another associated with changes in temperatures of all the parts of the cylinder-piston group and the same temperature stresses by almost linear dependencies.

For example, Prof A. K. Kostin [7] proposed the following expression of parameters for the evaluation of thermal stresses of the indirect piston and determination of the average thermal flow through cylinder surfaces being cooled:

$$\zeta = P_{max} \cdot \left(\frac{1}{\alpha}\right)^{0.88} \cdot (P_K \cdot C_m)^{0.5} \cdot n. \quad (4)$$

Other criteria of complex indirect thermal stresses (of the firm Rikardo, CNIDI, Prof. S. V. Kamkin, Prof. M. I. Fedorov, etc.), which can be used for the evaluation of the thermal condition of the parts of the cylinder-piston group, are also known. However, those are already sophisticated criteria of complex indirect thermal stresses, the determination of which requires parameters obtained during bench tests of the engine.

The following indirect criteria have been selected for the adaption of diesel engines of a diesel locomotive:

- $P_D = \frac{P_e}{D \cdot i}$  – prof Ginzburg criterion (applicable to diesel engines of a wide range of applications; load of parts is evaluated according to the “piston power”);
- $q_{II} = \left(\frac{1}{\alpha}\right)^{0.88} (P_K \cdot C_m)^{0.5}$  – applicable to diesel engines of a wide range of applications and types; specific heat flow to the piston bottom and cylinder head is evaluated according to the operating process parameters;
- $\Pi = (P_{me} \cdot t_r) / (P_{max} \cdot c_m)$  – criterion (applicable to marine diesel engines; the mechanical and thermal load of parts is evaluated according to the general energy indicators and working process parameters of the diesel engine);
- $q_R = \left(\frac{Gf}{F_{stum}}\right)^{0.8} \left(\frac{\varepsilon}{(\varepsilon - 1)} \cdot n \cdot S \cdot \rho_k\right)^{-0.3}$  – Ricard firm criterion (applicable to high-speed automotive diesel engines; specific heat flow to the piston bottom is evaluated according

to general energy and design parameters); here, in addition to the parameters of Formula (3):  $P_e$  – diesel engine power, kW;  $P_{me}$  – mean effective pressure, MPa;  $P_K$  – inflation air pressure, MPa;  $\alpha$  – excess air ratio;  $t_r$  – exhaust gas temperature, °C;  $c_m$  – mean piston speed, m/s;  $G_f$  – hourly fuel consumption, kg/h;  $F_{stum}$  – piston fuel area, m<sup>2</sup>;  $S$  – piston stroke, m;  $\varepsilon$  – compression degree;  $n$  – diesel engine rotations, min<sup>-1</sup>;  $\rho_K$  – inflation air density, kg/m<sup>3</sup>;  $i$  – number of cylinders.

The criterions applicable to marine and high-speed diesel engines and then they completely approved for other types of diesel engines, for loco diesel as well.

The structure of the criteria is adapted according to the diesel fuels of diesel locomotives under study, upon entering the corresponding values of the design parameters (see Table 1).

the diesel engine equal to 0,25; 0,15; 0,6, correspondingly (see Table 3).

### 3.2. Reliability evaluation of diesel engines of main-line diesel locomotives according to operating duration (life) indicators

Because of different methodology for the repair cycle rating of diesel engines installed on Lithuanian Railways diesel locomotives that are supplied by manufacturers from various countries, time to overhaul are evaluated by values of different indicators:

- Colomna Energy Service OU (Russia) diesel engines: 14D40 series (M62 and 2M62) – 8 640 000 l of fuel consumed; 2–2D49 series (M62K and 2M62K) – 1 500 000 km diesel locomotive run or 12 years;

Table 1. Indirect reliability criteria adapted for Lithuanian Railways diesel locomotive diesel engines

Criteria	Model			
	14D40	2-2D49	Caterpillar 3512B HD-SC	MTU16V4000R41
$P_D$	$\frac{P_e}{23 \cdot 12}$	$\frac{P_e}{26 \cdot 12}$	$\frac{P_e}{17 \cdot 12}$	$\frac{P_e}{16,5 \cdot 16}$
$\zeta$	$P_{\max} \cdot 10^{-1} \cdot \alpha^{-0.88} \cdot \left( P_K \cdot 10^{-1} \cdot \frac{0.3}{30} \right)^{0.5} \cdot n^{1.5}$	$P_{\max} \cdot 10^{-1} \cdot \alpha^{-0.88} \cdot \left( P_K \cdot 10^{-1} \cdot \frac{0.26}{30} \right)^{0.5} \cdot n^{1.5}$	$P_{\max} \cdot 10^{-1} \cdot \alpha^{-0.88} \cdot \left( P_K \cdot 10^{-1} \cdot \frac{0.215}{30} \right)^{0.5} \cdot n^{1.5}$	$P_{\max} \cdot 10^{-1} \cdot \alpha^{-0.88} \cdot \left( P_K \cdot 10^{-1} \cdot \frac{0.19}{30} \right)^{0.5} \cdot n^{1.5}$
$q_n$	$\alpha^{-0.88} \cdot \left( P_K \cdot 10^{-1} \cdot \frac{0.3 \cdot n}{30} \right)^{0.5}$	$\alpha^{-0.88} \cdot \left( P_K \cdot 10^{-1} \cdot \frac{0.26 \cdot n}{30} \right)^{0.5}$	$\alpha^{-0.88} \cdot \left( P_K \cdot 10^{-1} \cdot \frac{0.215 \cdot n}{30} \right)^{0.5}$	$\alpha^{-0.88} \cdot \left( P_K \cdot 10^{-1} \cdot \frac{0.19 \cdot n}{30} \right)^{0.5}$
$\Pi$	$\frac{P_{me}(T_r - 273)}{P_{\max} \left( \frac{0.3 \cdot n}{30} \right)}$	$\frac{P_{me}(T_r - 273)}{P_{\max} \left( \frac{0.26 \cdot n}{30} \right)}$	$\frac{P_{me}(T_r - 273)}{P_{\max} \left( \frac{0.215 \cdot n}{30} \right)}$	$\frac{P_{me}(T_r - 273)}{P_{\max} \left( \frac{0.19 \cdot n}{30} \right)}$
$q_R$	$\left( \frac{G_f}{0.0415} \right)^{0.8} \cdot \left( 0.322 \cdot n \cdot 348.4 \cdot \frac{P_K}{T_K} \right)^{-0.3}$	$\left( \frac{G_f}{0.0531} \right)^{0.8} \cdot \left( 0.278 \cdot n \cdot 348.4 \cdot \frac{P_K}{T_K} \right)^{-0.3}$	$\left( \frac{G_f}{0.0227} \right)^{0.8} \cdot \left( 0.23 \cdot n \cdot 348.4 \cdot \frac{P_K}{T_K} \right)^{-0.3}$	$\left( \frac{G_f}{0.0214} \right)^{0.8} \cdot \left( 0.203 \cdot n \cdot 348.4 \cdot \frac{P_K}{T_K} \right)^{-0.3}$

### 3.1. Approbation of reliability criteria

The criteria have been approbated with the use of the locomotive diesel engine operating (testing) load cycle structure according to ISO 8178-4(F) (see Table 2).

Table 2. Locomotive diesel engine operating (testing) load cycle structure according to ISO 8178-4(F)

Power (load), %	100 %	50 %	No-load run
Rotations, %		transient	
Relative part of operating duration	0.25	0.15	0.60

The values of the criteria are calculated according to the parameters of the diesel locomotive operating characteristic for the modes of nominal power, 50 % load, and no-load run. For example, the values  $\xi_{100\%}$ ,  $\xi_{50\%}$ , and  $\xi_{no-load}$  are calculated for the criterion  $\zeta$ .

The integral value of the criterion characteristic to the whole operating (testing) cycle is determined according to the following formula:  $\xi = \xi_{100\%} \cdot \tau_{100\%} + \xi_{50\%} \cdot \tau_{50\%} + \xi_{no-load} \cdot \tau_{no-load}$ , where

$\xi_{100\%}$ ,  $\tau_{50\%}$ ,  $\tau_{no-load}$  – the relative parts of the operating period of

- Zeppelin – Cat Power Systems Corporation (Germany – USA), Caterpillar 3512B HD-SC series (2M62M and 2M62UM) diesel engines – 5 840 000 l of fuel consumed;
- MTU Friedrichshafen GmbH (Germany), MTU16V4000R41 series (ER 20CF) diesel engines – 48 000 motor-hour or 18 years.

The data provided by these manufacturers and determined during operation were expressed in operating years on the basis of statistical average values of Lithuanian Railways determined during operation].

As a result (on the basis of the statistical data concerning the consumption of 1 500 000 l by a diesel engine of a diesel locomotive in 15 000 motor-hour), the time to overhaul of M62 and 2M62 type diesel locomotive serial 14D40 type diesel engines is 8 640 motor-hour or 14.8 years.

The operating life of 2–2D49 series diesel engines of the same manufacturer installed on remotorised M62K and 2M62K type diesel locomotives is 78 840 motor-hour or 13.5 years (on the basis of the statistical run operation average value of the diesel engine, t. y. 100 000 km per year).

When performing calculations for the diesel engines of Zeppelin – Cat Power Systems Corporation for modernised 2M62M and 2M62UM type diesel locomotives, different fuel consumption



Table 3. The values of the reliability criteria of diesel engines of Lithuanian Railways freight diesel locomotives calculated in accordance with the operating trial cycle modes (ISO 8178/4)

Model engines	$P_d$	$\zeta$	$q_{II}$	$\Pi$	$q_R$	Load
MTU16V4000R41	10.1	32230	1.133	5.466	311.2	100 %
	5.06	11980	0.815	7.079	209	50 %
	0.606	655	0.214	6.226	66.5	No-load
	3.65	10245	0.533	6.164	149.1	Average cycle values
Caterpillar 3512B HD-SC	8.33	24738	1.004	5.559	274.3	100 %
	4.1	8300	0.78	6.478	147.1	50 %
	0.49	548	0.203	3.835	55.5	No-load
	2.81	7758	0.489	4.663	123.9	Average cycle values
2-2D49	4.712	6878	0.69	7.392	143.7	100 %
	2.35	2805	0.594	7.208	101.4	50 %
	0.484	308	0.193	6.56	81.2	No-load
	1.82	2325	0.377	7.1380	99.62	Average cycle values
14D40	2.663	4965	0.602	4.8	214.73	100 %
	1.34	1890	0.427	3.83	129.4	50 %
	0.274	484	0.242	3.04	104	No-load
	1.31*	1815	0.360	3.6	135.4	Average cycle values

\*) In the formula for the value of prof Ginsburg  $P_d$  applicable to a two-stroke 14D40 diesel engine a multiplier 0.5 is introduced as compared to four-stroke diesel engines.

efficiency indicators of 14D40 and 3512B HD-SC diesel engines were taken into account. When operating in the nominal mode, the specific effective fuel consumption of Caterpillar 3512B HD-SC diesel engine is by 8 % lower than that of 14D40. However, these parameters do not reveal the real operating comparative diesel consumption levels because diesel engines of diesel locomotives operate at low-load and no-load modes for a major part of the operating cycle duration (up to (up to 50–60 %).

The use of fuel injection and air supply control electronic systems (as in Caterpillar 3512B HD-SC and MTU16V4000R41 diesel engines) in principle improves the fuel consumption efficiency indicators of the diesel engine.

Comparative operating fuel consumption levels of diesel locomotives calculated for 100 000 tkm have been evaluated on the basis of the tests performed by Lithuanian Railways on one of the railway lines (when changing the weight of the train from 5 000 t to 3 000 t, the number of axes from 164 to 284 units, etc.).

The obtained fuel consumption of diesel engines of M62M diesel locomotives were by ~24 % lower compared to 14D40 diesel engine installed on M62 diesel locomotives (5 diesel locomotives of each make were used in the tests). On the other hand, based on the weight and length standards of Lithuanian Railways for freight train units, the capacity of M62M locomotive is by 25–20 % higher than that of M62M (M62). It means that under Lithuanian Railways transportation conditions, higher fuel consumption efficiency of M62M diesel locomotive is “compensated” by higher diesel engine load. The obtained result is 12.4 years or, if recalculated into operating duration, 59 400 motor-hour.

For MTU16V4000R41 series diesel engines of new ER 20CF type diesel locomotives manufactured by MTU Friedrichshafen GmbH, the manufacturers guarantee interpretations of a span of 48 000 motor-hour or 18 years of operation to major overhaul. 18 years of operation is only possible subject to compliance with the condition set by the manufacturer that the diesel engines will operate in accordance with the standard ISO 8178 – 4, F load cycle. Besides, according to the recalculation of the average daily operating time of a locomotive, the obtained proportion of 48000 motor-hour/18 years will be maintained only provided that the diesel engine of the diesel locomotive works

for not more than 7 h per day, while the average daily working time of Lithuanian Railways main-line freight locomotives reaches 16 h per day, i.e. double the time stipulated by the manufacturer. For these reasons, as a result of the performed recalculation of the time span to major overhaul under the standard applicable to other diesel engines, it was established that the operating life shortens from the value of 18 years to 8.2 years.

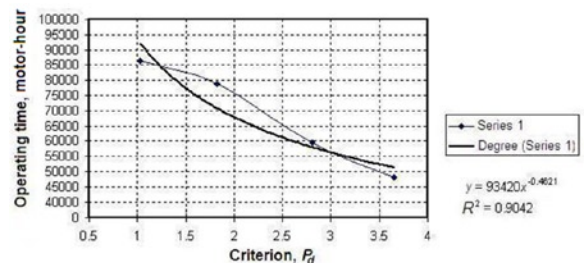


Fig. 1. Result of the adaptation of  $P_d$  criterion for diesel engines of Lithuanian Railways freight diesel locomotives

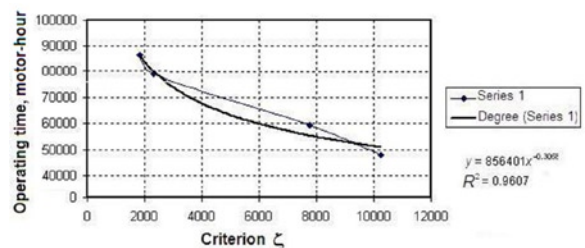


Fig. 2. Result of the adaptation of  $\zeta$  criterion for diesel engines of Lithuanian Railways freight diesel locomotives

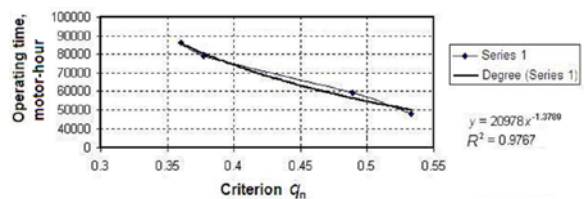


Fig. 3. Result of the adaptation of  $q_{II}$  criterion for diesel engines of Lithuanian Railways freight diesel locomotives

### 3.3. Grounds of the methodology for the forecasting of the operating life of diesel engines of freight diesel locomotives

The logical and technological compatibility of the methodology being developed with the train departure planning and scheduling technologies of Lithuanian Railways – computer mathematical simulation, whose functioning algorithm is based on rolling stock traction calculations, was assumed as one of its basic principles [8].

The main aspects of the methodology and components are sche-

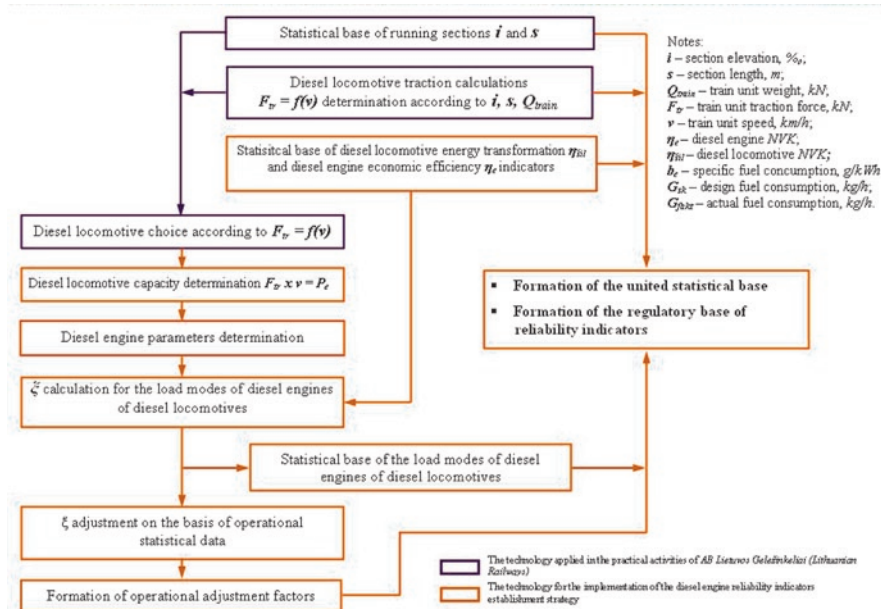


Fig. 4. The principal diagram of the methodology for the establishment of reliability indicators of diesel engines installed on diesel locomotives

matically presented on Fig. 4.

Therefore, on the basis of the graphical dependencies of all parameters of indirect criteria of diesel engines installed on diesel locomotives ( $x_e = f(P_e, n, \text{Controler position})$ ) values of  $\xi$  could be calculated exactly.

Depending on the load modes of the diesel locomotive (which, alternatively, could also be recorded or simulated for statistical purposes by the computer after modifying the PC programme used by Lithuanian Railways for departure planning), the integral  $\xi$  criterion for the diesel locomotive for operation at segments of the corresponding section is determined.

Because of the impact of transient operating modes on reliability indicators, adjustment factors are introduced on the basis of operational data.

The implementation of the methodology provides for the following:

- 1) Mathematical computer simulation of the operating characteristics of diesel engines installed on 14D40, 2-2D49, Caterpillar

3512B HD-SC, and MTU16V4000R41 diesel locomotives and comparison of the obtained results with experimental data;

- 2) Selection of indirect criteria of diesel engines installed on diesel locomotives and their processing for the models of the fleet of Lithuanian Railways;
- 3) Development of an algorithm for the calculation of operational reliability indicators of diesel engines installed on diesel locomotives in order to achieve its compatibility with the new information technologies of Lithuanian Railways;
- 4) Determination of reliability indicators of diesel engines installed on diesel locomotives and the development

and testing of a programming mathematical simulation complex for the forecasting of operating life under operating conditions.

Outcome of the investigation will be published in other publications.

## 4. Conclusions

1. Evaluation of a whole versatility of statistical data, during a relatively short operating period of new diesel locomotives, showed that methods of computer simulation and similarity theory should be applied for the determination of the reliability of operating parameters and forecasting of operating life of diesel engines installed on diesel locomotives, i.e. with the use of practically approved thermal and mechanical load criteria of parts, which define the design and operating process particularities of diesel engines under conditions similar to those under which diesel engines are operated by Lithuanian Railways. The resistance of the parts of the cylinder-piston group (CPG) and slider-crank mechanism (SCM) to wear is one of the main criteria of their durability preconditioning their operating work time, i.e. operating life. By analysing the indicators of the operating reliability of diesel engines on this basis, the dependency between external environmental and diesel locomotive operating factors and the character of wear of the parts contained in the CPG and SCM of a diesel engine has been studied.

2. The adequacy of applying indirect mechanical and thermal load criteria of parts of diesel engines installed on diesel locomotives for diesel engines installed on diesel locomotives of AB "Lietuvos Gelezinkeliai" Lithuanian Railways is proved by the obtained strong correlation dependency (determination coefficient  $R^2 \approx 0.95$ ) between these criteria and the operating life of diesel engines (old modernised and new ones).
3. On the basis of the performed analytical studies, a methodology for the mathematical simulation of operating indicators of diesel engines installed on diesel locomotives, including reliability ones, has been developed on the basis of the classic principals of rolling stock traction calculations.

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