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Research of operational dependability of automotive engines

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Abstract. *The problem of increasing the dependability of the engine, which is the most complex and expensive unit of an automotive vehicle, cannot be solved without objective and reliable information on the failures and malfunctions of its components, their causes, actual life, as well as the factors affecting such indicators in real operational conditions. Manufacturing factories do not always have such information, hence design deficiency failures associated with design and development flaws are among the most common causes of loss of engine operability.* **The aim** *of this paper is to study the engine operational dependability using the results of their maintenance and repair.* **The methods** *are based on operational tests of engines that yield the most complete and objective information on their dependability, as they were conducted in typical operational conditions of automobile operating companies in the course of vehicle maintenance and repair. The results of the studies processed with the standard Statistica 6.0 are represented in the form the statistical evaluations of the dependability of primary structural engine components (times to failure, changes in the probability of no-failure depending on the travelled distance). The analysis of the obtained information allows estimating the level of actual dependability of the engine, identifying design flaws, developing specific measures aiming to increase operational dependability. Information obtained during such tests is useful not only to the engine manufacturers, but to the operators as well, as it enables a scientific substantiation of the norms of operability. For the purpose of identification and localization in the process of maintenance and repair of specific engine malfunctions, the paper substantiates a set of diagnostic parameters and their standard values.* **Conclusions.** *The research allowed elaborating a set of diagnostic parameters for evaluation of the technical condition of primary engine systems (cylinder-piston group, crank and gas distributing mechanisms) that define and limit its dependability. The application of the findings in the automobile maintenance and repair processes enables a significant improvement of the engines' operational dependability and reduction of the costs of ensuring their operability.*

Keywords: *engine, automobile, dependability, failure, operation time, structural parameter, diagnostic parameter, technical condition.*

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To solve the problem of ensuring a high dependability level and operability of technical systems, different types of information on their operation conditions, acting loads, mode and causes of failures and malfunctions are required. The availability of such information is a prerequisite of the improvement of system dependability at all lifecycle stages and the basis for the development of measures to improve the design, processes of its manufacture and operation. This all applies to the internal-combustion engine that is the most complex and expensive unit of a vehicle, which account for up to 20% of all its failures.

Engines manufacturing factories do not always have reliable information on malfunctions arising during operation, causes of failures, operation time to limit state and other indicators characterizing operating dependability of their products. As a result, in actual operating conditions, among causes of engine failures, there are design deficiency failures caused by the imperfection of their design and engineering.

The tests (development, research, acceptance, validation, etc.) are a source of reliable information on engines dependability, as well as any other mechanism and system

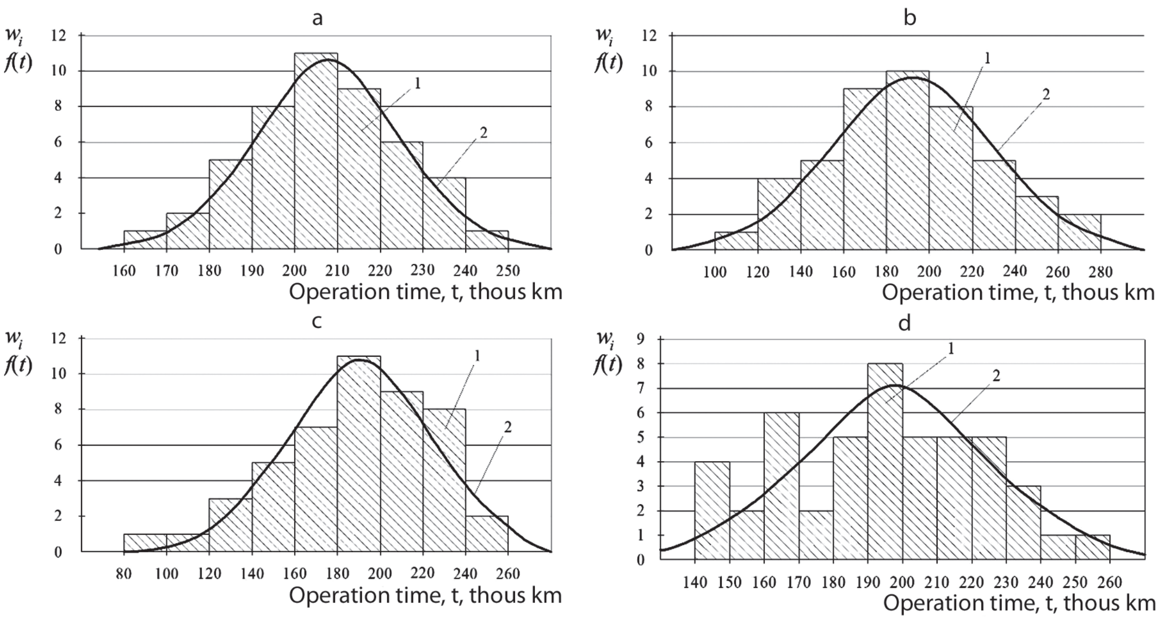

Figure 1. Histograms (1) and theoretical curves (2) of times to failure distribution: a) engine block; b) cylinder head; c) piston block; d) cranked shaft

Table 1. Statistical estimates of the numerical characteristics of the engines dependability

no.	Names of structural engine components	Mean liftime t_{mlt}, thous. km	Mean square deviation, y, thous. km	Variation coefficient, н
1	Engine block	203.7	34.5	0.169
2	Cranked shaft	198.4	39.2	0.198
3	Connection shaft	141.8	41.7	0.294
4	Distributive shaft	194.6	26.8	0.138
5	Piston block	191.6	35.3	0.184
6	Piston rings	148.2	45.2	0.304
7	Bottom-end bearing	164.0	41.4	0.254
8	Cranked shaft bearing	166.0	40.6	0.245
9	Connecting rod bush	195.9	52.9	0.270
10	Piston pin	186.2	37.2	0.200
11	Valve guide	154.6	34.0	0.220
12	Deflation valve	169.0	34.8	0.206
13	Hydraulic tappet	131.8	39.8	0.302
14	Cylinder head	193.6	39.0	0.201

of the vehicle. The most objective and exhaustive information on the engines dependability is produced by operation tests that are carried out in typical vehicle operating conditions. Information obtained during such tests is useful not only for the engine manufacturers, but for the operators as well, as it enables a scientific substantiation of the norms of operability.

As part of this paper, a research on engines dependability was carried out in actual operating conditions with registration of condition data during technical maintenance and repair of vehicles. The ZMZ-4063.10 engine produced by the Zavolzhsky engine plant and installed on the GAZelle family vehicles was taken as the object of research. A large amount of information on malfunctions and engines failures arising during vehicles operation, has been collected.

The findings on the operation dependability of primary structural engine components, processed with the standard program Statistica 6.0, are presented in Table 1, and partially in the forms of histograms and theoretical curves of times to failure distribution in Figure 1.

The curves types as well as the calculated values of variation coefficient н show that distribution of times to failure of the engine components is described by the normal law. Test of the hypothesis on experimental data belonging to the normal probability with the Pearson fitting criterion χ^2 confirmed its validity.

One of the main indicators that evaluates the dependability of structural engine components is the probability of its fail-safe operation $P(t)$ or failure $F(t)$ within the limits of operating time. Table 2 shows the processing results of statistical data on dependability of primary components of the studied engines, which clearly show the change of probability of their failures in operating time t.

Analyzing the data presented in Table 2, some conclusions can be made regarding the operation dependability of components of the studied engines. The probability of fail-safe operation of components for the initial intervals of operating time from 0 to 90 thous. km is at a sufficiently high level. During this period of operation there is a low probability of failure of the deflation valves and hydraulic tappets of gas distribution mechanism which are exposed to high mechanical and thermal loads during engine operation. The probability of fail-safe operation of connection shaft, cylinder head gasket, piston rings, bottom-end bearing and valve guide decreases significantly by the operating time of 154 thous. km. Within the interval of operation time from 154 to 218 thous. km, there is a sharp increase in the engine failure probability which for different components ranges from $F(t) = 0.620$ (connecting rod bush) to $F(t) = 0.995$ (deflation valve). Practically all engine components exhaust their lifespan by the operating time of 250 thous. km. By this operating time the failure probability of the base component, the engine block, reaches $F(t) = 0.911$, which indicates the requirement for an overhaul or decommissioning.

Among the reasons for this level of the engine operation dependability in addition to the design and manufacture factors, the effects of the operating conditions should be noted: road condition, storage, environmental conditions, infrastructure and others. The operating conditions include the maintenance system with control and diagnostic, preventive and repair measures aimed at ensuring engine efficiency.

To ensure reliable engine operation and reduce the cost of maintenance operations after failures, most of them must be prevented as part of scheduled maintenance. Therefore, during maintenance, it is required to have the information on the engine technical condition, on hidden and imminent

Table 2. Probabilities of failure of primary engine components ZMZ-4063 in operating time

no.	Component title	Probability of failure $F(t)$ in time, thous. km						
		58	90	122	154	186	218	250
1	Engine block	0	0.001	0.009	0.075	0.304	0.661	0.911
2	Cranked shaft	0	0	0.004	0.065	0.336	0.749	0.961
3	Connection shaft	0.022	0.107	0.317	0.615	0.856	0.966	0.995
4	Distributive shaft	0	0	0.003	0.065	0.375	0.810	0.981
5	Piston block	0	0.002	0.024	0.143	0.437	0.773	0.951
6	Piston rings	0.023	0.099	0.281	0.551	0.799	0.939	0.988
7	Bottom-end bearing	0.005	0.037	0.161	0.405	0.702	0.904	0.981
8	Cranked shaft bearing	0.004	0.030	0.139	0.384	0.689	0.901	0.981
9	Connecting rod bush	0.005	0.023	0.081	0.214	0.426	0.620	0.847
10	Piston pin	0	0.005	0.042	0.194	0.438	0.804	0.957
11	Valve guide	0.002	0.031	0.169	0.493	0.807	0.969	0.997
12	Deflation valve	0.053	0.221	0.5314	0.827	0.962	0.995	0.999
13	Hydraulic tappet	0.071	0.229	0.493	0.759	0.923	0.984	0.998
14	Cylinder head	0	0.001	0.033	0.155	0.423	0.735	0.926
15	Cylinder head gasket	0.006	0.069	0.332	0.729	0.951	0.996	0.999

Table 3. Structural and evaluating diagnostic parameters of the ZMZ-4063 engine

no.	Diagnostic parameter	Structural parameter
1	Pressure at the end of a compression stroke, S_1	• Clearance between the ring and the 1-st compression ring by groove width, Y_1 • Clearance in gap of the 1-st compression ring, Y_2 • Clearance between the ring and the 2-nd compression ring by groove width, Y_3 • Clearance in gap of the 2-nd compression ring, Y_4 • Clearance between the piston and the engine block, Y_5 • Valve plug-to-guide bush clearance, Y_6 • Valve plug-to-guide bush clearance Y_7
2	Value of relative air leaking at the piston position at top dead center (TDC), S_2	• Clearance between the ring and the 1-st compression ring by groove width, Y_1 • Clearance in gap of the 1-st compression ring. Y_2 • Clearance between the ring and the 2-nd compression ring by groove width, Y_3 • Clearance in gap of the 2-nd compression ring, Y_4 • Clearance between the piston and the engine block, Y_5 • Valve plug-to-guide bush clearance, Y_6 • Valve plug-to-guide bush clearance, Y_7
3	Flow rate of oil samp gas, S_3	• Clearance between the ring and the 1-st compression ring by groove width, Y_1 • Clearance in gap of the 1-st compression ring, Y_2 • Clearance between the ring and the 2-nd compression ring by groove width, Y_3 • Clearance in gap of the 2-nd compression ring, Y_4 • Clearance between the piston and the engine block, Y_5
4	Pressure in the main oil distributing passage, S_4	• Crank bearing-to-bushing clearance, Y_8 • Crankshaft neck-to-bushing clearance, Y_9 • Bush bearing of connection shaft-to-shaft neck clearance, Y_{10} • Bearing of distributive shaft-to-shaft neck clearance, Y_{11}

failures in the engine, causes of abnormal operations etc. Such information can be obtained during engine diagnostics by measuring the parameters that characterize the engine condition and comparing them with the standard values.

The variety and significant number of diagnostic parameters that describe the internal combustion engine condition necessitates the selection of the most informative ones that are characterized by the sensitivity of changes in their values depending on the changes of structural parameters and by unambiguous diagnostics. The set of diagnostic parameters of engine technicalcondition evaluation was substantiated based on the analysis of structural components failures and malfunctions statistics, trends of changes in the technical condition of mechanisms and units, developed structural diagrams of primary engine systems that define and limit its lifetime (cylinder-piston group, crank mechanism, valve timing gear). Equally important condition for the choice of diagnostic parameters is the ability to evaluate the engine remaining lifetime using their current values.

Therefore, such parameters as the analysis of the qualitative and quantitative composition of wear particles in oil, fuel burn rate, uncharging in combustion chamber, content of harmful substances in the exhaust fumes and others are not informative or require significant time of diagnosis. Table 3 shows the diagnostic parameters that meet the requirements, as well as a list of structural parameters that they evaluate.

Table 4 shows the standard nominal and limit values of diagnostic parameters specified by the manufacturer for the ZMZ-4061.10, 4063.10, 40637.10 engines.

Operational tests of engines dependability involved the effect of the clearance values given in Table 3 on the diagnostic parameters that evaluate them. For this purpose, before the second maintenance, the technical condition of the mechanical system of the internal combustion engine

Table 4. Standard values of diagnostic parameters assessing the engine condition

no.	Diagnostic parameter	Nominal value	Limit value
1	Pressure at the end of a compression stroke, kp/cm^2	12	9.6
2	Value of relative air leaking at the piston position at top dead center (TDC), kp/cm^2 for at least 5 sec	decrease from 1.5 to 1	decrease from 1.5 to 0.75
3	Flow rate of oil samp gas at 4000 min^{-1}, for at least l/min	22	62
4	Value of pressure in the main oil distributing passage, kp/cm^2: at 2500 min^{-1} at 700-800 min^{-1}	 5.0 –	 3.0 1.1

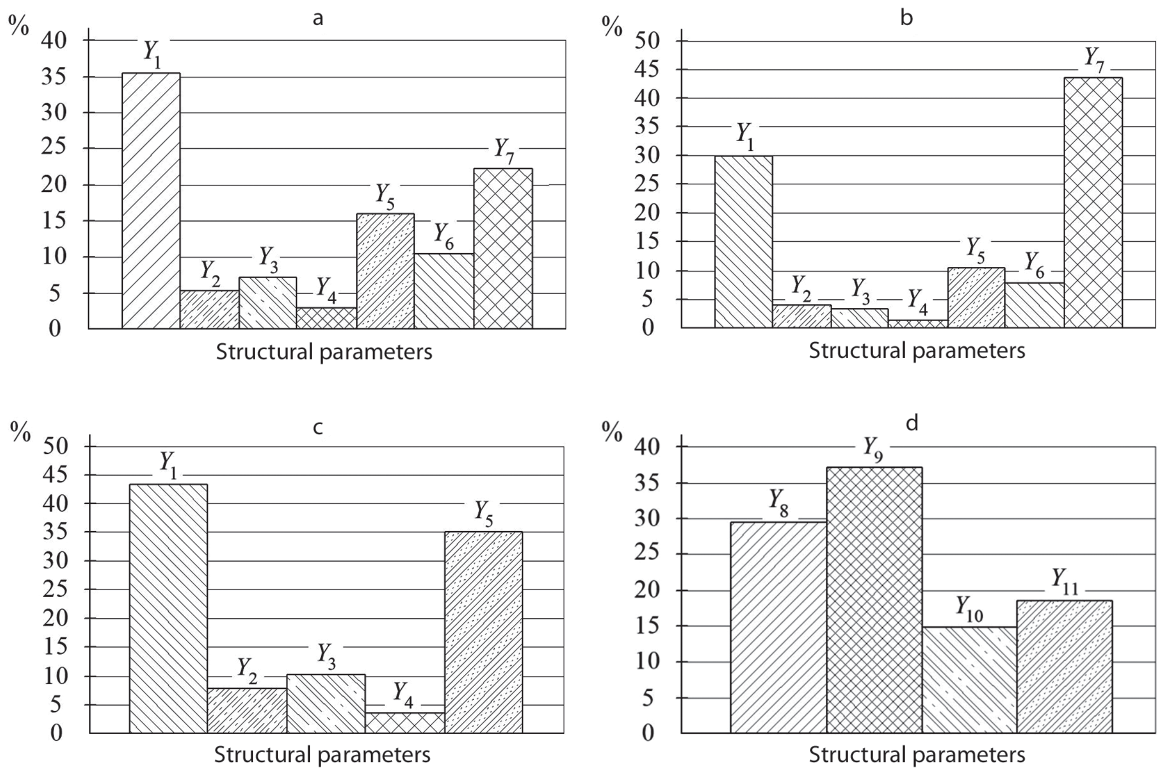

Figure 2. The degree of the effect of structural parameters on the diagnostic parameters: a) pressure at the end of a compression stroke; b)relative air leaking; c) flow rate of oil samp gas; d) pressure in the main oil distributing passage

was diagnosed. In case when values of diagnostic parameters exceeded the maximum permissible ones, the engines were sent to the repair department where they were partially or, if necessary, completely disassembled and the corresponding clearances measured. The collected measurement data was organized in a database and based on the results of its processing regressive models were built that characterized the effect of the structural parameters Y of the engine's systems on the diagnostic parameters S chosen for their evaluation:

S_1 = 0.355 Y_1 +0.054 Y_2 +0.073 Y_3 +0.031 Y_4 +0.16 Y_5 +0.105 Y_6 +0.223 Y_7;

S_2 = 0.298 Y_1 +0.037 Y_2 +0.033 Y_3 +0.015 Y_4 +0.104 Y_5 +0.077 Y_6 +0.436 Y_7;

S_3 = 0.434 Y_1 +0.078 Y_2 +0.103 Y_3 +0.035 Y_4 +0.350 Y_5;

S_4 = 0.294 Y_8 +0.372 Y_9 +0.148 Y_{10} +0.186 Y_{11}.

The findings showed that the degree of the effect of the same structural parameters on the diagnostic parameters chosen for the evaluation of the technical condition of internal combustion engines has different values. For example, the clearance between the ring and the 1-st compression ring by groove width (Y_1) has a dominant effect on diagnostic parameters S_1, pressure at the end of a compression stroke (35.5%) and S_3, flow rate of oil samp gas (43.4%). The structural parameter Y_7, valve-to-valve seat (43.6%) has the greatest impact on the relative pressed air leaking S_2. The crankshaft neck-to-bushing clearance Y_9 (37.2%) and crank bearing-to-bushing clearance Y_8 (29.4%) has an effect on diagnostic parameter S_4, pressure in the main oil distributing passage. Figure 2 shows the degree of the effect of clearance on the diagnostic parameters (in percentage points) in the form of diagrams.

The obtained dependences between the diagnostic and structural parameters allow identifying the most probable failures of the engine's mechanical systems and making the required list and algorithm of technical measures to restore their operability. For example, if the diagnostic parameter S_2 (relative air leaking at the piston position at top dead center) is out of tolerances, it most likely indicates increased wear of deflation valves, pistons and compression rings and in to a lesser degree changes in other engine components.

In case of deviation from standard values of diagnostic parameter S_1 (pressure at the end of a compression stroke) the most probable malfunctions are wear in the piston-to-compression ring, valve-to-valve seat and piston-to-engine block systems. Out of tolerances diagnostic parameter S_4 (pressure in the main oil distributing passage) indicates wear in the crankshaft neck-to-bearing bushing, crank bearing-to-bottom-end bearing systems, as well as wear of the necks of connection and distributive shafts.

The findings regarding engine operational dependability allow optimizing the system of their maintenance and repair, developing an algorithm for identification and elimination of occurring malfunctions. For example, up to the operating time of 90 thous. km there is no need to verify the condition of an engine's mechanical systems, since the probability of their fail-safe operation is at a sufficiently high level. In the operation time interval between 90 and 122 thous. km, it is recommended to perform deep diagnostics of gas distribution mechanism couplings, as in this interval there is a significant increase of failure probabilities of its components (deflation valve, hydraulic tappet, cylinder head gasket). Starting from the operation time of 122 thous. km the technical condition of all engine structural parameters must be diagnosed.

The application of the findings in the processes of maintenance and repair of vehicles allows increasing the operational dependability of engines and reducing the costs associated with insuring their operability.

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