

Досліджено можливості діагностування циліндро-поршневої групи дизеля КамАЗ-740.63-400 вантажних автомобілів КамАЗ-6460 на 60 тис. км їх пробігу. Обрано наступні діагностичні параметри: тиск картерних газів, компресійні та вакууметричні властивості циліндро-поршневої групи. Особливість цих спряжень полягає в тому, що підтримується нормальний процес горіння в циліндрах дизеля, а також його ресурс. Виявлено граничні межі для діагностування тиску картерних газів 2,39–2,41 КПа. За даними тиску картерних газів для досліджуваних вантажних автомобілів несправності виявлені на пробігах: 36 тис. км, 48 тис. км, 60 тис. км. Враховуючи правила оцінки характеристик несправностей за компресією, мінімальне значення компресії для дизелів становила 30,05 МПа, або її різниця між циліндрами не перевищувала 10–12 %. За даними компресії виявлено несправності на 48 тис. км та 60 тис. км дослідного напрацювання. Виявлено граничні межі зношування за вакууметричними параметрами: максимальний вакуум – 69–86 КПа; залишковий вакуум – 26–41 КПа. За контролем вакууметричних властивостей циліндро-поршневої групи виявлено несправності дизелів для інтервалу пробігу 36–60 тис. км.

Використовуючи ентропійний підхід, проведено оцінку інформативності відповідних діагностичних параметрів в бітах. Рівень інформативності тиску картерних газів становить 0,329 біт, компресія в циліндрах – 0,249 біт, вакууметричні показники – 0,582 біт.

Дані дослідження дають змогу раціонально формувати комплекси діагностування стану дизеля під час технічної експлуатації, а також визначити передумови розвитку несправностей. Отримані дані важливі для транспортних та сервісних підприємств та компаній, що займаються вантажними автомобілями.

Ключові слова: дизель, діагностика, компресія, циліндро-поршнева група, тиск картерних газів, вакууметричні властивості спряження, ентропія, інформативність

# DEVELOPMENT OF A SYSTEM FOR DETERMINING THE INFORMATIVENESS OF THE DIAGNOSING PARAMETERS FOR A CYLINDER-PISTON GROUP IN THE DIESEL ENGINE DURING OPERATION

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## 1. Introduction

The cylinder-piston group has a significant role in the structure of the diesel engine as it ensures its basic working characteristic during operation: compression of the working mixture to the required degree to enable a steady process of its combustion [1]. Given the importance of this characteristic, as well as the significant cost of service operations, it

is desirable to reliably assess those patterns that reflect the technical condition of mated parts over the operational period of the diesel engine trucks [2].

Mated parts within a cylinder-piston group operate under severe operating conditions: loading the parts is dynamic, the temperature is distributed non-evenly, and has high values, from 150 °C [3]. The operating conditions of the cylinder piston group are also subject to high operation-

al requirements for ensuring the tightness of the working chamber [4], the high tribological efficiency of the mated parts “sleeve–ring–piston” and “sleeve–piston”.

The functioning of a cylinder-piston group in a large degree affects the service cost of the diesel engine, which depends on the timely and accurate determination of its technical condition. This corresponds to the principles of operational reliability, which characterize this group of mated parts. In such circumstances, it is advisable to carry out timely maintenance as service recommendations do not always provide complete and justified principles. Because of this, vehicle owners face significant financial costs, especially for commercial vehicles, as these vehicles operate in the logistic chains on a “just-in-time” basis [5]. Therefore, every hour of idle truck brings its owner significant losses. The worst case in the logistics chain is the issue of sudden breakdowns when the contract involving a given vehicle has not been fulfilled [6, 7].

Under current conditions, this issue is resolved by improving maintenance processes based on an intelligent diagnosing database. However, as it turned out, this approach is associated with significant scientific and technical difficulties as it is difficult to describe the function of technical condition of various systems and assemblies, as well as their mated parts. The difficulties are due to a significant number of diagnosing operations and parameters that have their physical nature and dimensionality [8]. Ultimately, it is also desirable to predict the technical condition of cars’ systems and assemblies with the possibility of accounting for their significance during exploitation.

Given the operating and service conditions related to the cylinder-piston group, it is necessary to perform diagnosing operations that make it possible to determine its technical condition and to devise an approach to estimating the informativeness of the introduced diagnosing parameters. Determining the informativeness of diagnosing parameters during the technical exploitation of vehicles is undoubtedly the relevant scientific-technical task related to the technical exploitation of trucks.

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## 2. Literature review and problem statement

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Tough operating conditions of the cylinder-piston group predetermine the wear of its mated parts. At the same time, there is the increased intensity of the piston ring wear, as well as working surfaces of sleeves and pistons, which, in turn, could change the conditions of ignition in a space over the piston. Changing the ignition conditions worsens the conditions for the normal operation of other diesel engine systems, which is clearly evident when using different fuels for the powerplant of a vehicle [9]. The combustion conditions are maintained by the formed rational system of control and diagnosing, which is not provided in modern service recommendations in full. Untimely detection of malfunctions leads to the emergence of sudden failures, which are dangerous in the technical operation of trucks. In cases of sudden failure in the technical exploitation, various tribological additives are additionally used to improve the mated parts’ resource [10]. The use of these additives when introducing them in the diesel engines’ oil is not described in detail, so it is necessary to further build a rational diagnosing system, which would reflect changes in the technical condition of the mated parts within a cylinder-piston group.

Measuring equipment requires the development of vacuum-electric modules [11] to reliably control the airflows. Moreover, it is necessary to design equipment that would be responsible for the accuracy and reliability of diagnosing parameter values, as well as in service. Appropriate equipment must be reasonably priced. The optimization of value indicators and financial flows, as well as services, at enterprises that operate in the market conditions are important tasks for every moment of business functioning [12]. Special attention should be paid to the rational functioning of service providers in order not to increase the operational cost of powerplants and vehicles in general. To increase the resource of parts of powerplants at their low cost, it is proposed to use metallic-polymeric materials [13], as well as polymeric materials with high modular fillers [14], in their manufacture. Matrices of the parts’ material are made of low-cost materials and have minor technical indicators for the temperature of their use; it is, therefore, needed to implement a system of timely detection of defective work in the mated parts of machine assemblies. The development of a diagnosing system of various mated parts is important and necessary in the implementation of repair operations and strengthening the parts’ resource [15]. Performing strengthening operations is important and possible for use after the warranty period of operation of transportation machines, while over remaining periods the reliability is maintained by operational maintenance methods. Traditional service methods make it possible to perform both continuous and periodic diagnosing [16]. The substantiation of the frequency of diagnosing information reading and its acquisition during the operation of machine assemblies is required.

A special indicator of the surface wear of the mated cylinders in a cylinder-piston group of the diesel engine is a place of wear at the top point of a piston’s rise in the cylinder [17], based on which one can discard of defective parts by using an endoscope. The authors did not account for the specificity of exploitation and the influence exerted by external factors on the cylinder’s working surface. In agriculture engineering, the influence of mechatronic sensors in the control over operating parameters of machines has considerably increased recently [18]. These sensors operate under dusty conditions and are costly for implementing the monitoring systems. To reduce the cost of such systems, agricultural engineering introduces logical pneumatic elements for the qualitative maintenance of their working functions [19]. These systems require significant expenditures to control them during operation and training of specialists who service them. A research into the pneumatic streams and objects was carried out with the help of compressor-measuring equipment [20]; the authors, however, did not develop the system of monitoring and diagnosing for this equipment.

A change in the informative indicators of the diesel engines was considered in converting these power units to a mixture of diesel fuel with fusel oils [21]. In that case, more attention should be paid to the compression diagnosing, so that the traction characteristics of the diesel engine remain within the norm over the maximum vehicle mileage. It is possible to increase the operational resource of machine power units by using structural fluoroplastic [22] and carbon plastics [23]. These materials have proven effective in the manufacture of parts that are operated in the conditions of the dusty environment; however, their use under a gradient sign-changing load in the diesel engines is not possible due to the limited temperature and mechanical characteristics of the materi-

al. Significant contribution to increasing the reliability of components of machines' power units is rendered by various additives to working oils [24], as well as the compositions of synthetic and natural materials and tribologically active additives [25]. When using various additives, it is necessary to ensure a procedure of control over the technical condition of the mated parts as there may come a moment of the activation of their working surfaces' wear by the additives used. Modeling the patterns of wear of cylindrical supports [26] makes it possible to estimate and then forecast the mated parts in the power units of trucks. For a proper application of a given approach, it is necessary to assess the structural parameters of resource-defining mated parts in the process of exploitation.

As regards the technical service, it is important to evaluate diversified technical information qualitatively. Using mathematical methods for evaluating resultant functions is an important tool in analyzing complex systems [17]. However, in the field of technical exploitation, it is necessary to adapt the methodology of information theory to the real possibility of developing the concept of intellectualization. Technical exploitation is very closely intertwined with the field of tribology, the wear of machine parts [28], as wear models make it possible to better understand the surface processes that occur in the examined mated parts. Determining wear patterns of working surfaces of mated parts creates rational conditions for the choice of diagnosing methods but it is advisable to additionally assess the operational characteristics of mated parts in general. The most effective method in the technical operation has been the selection of materials for mated parts within a cylinder-piston group [30], as well as providing the necessary lubricating environment for the operating period of power units of vehicles [31]. Adjustment of operating characteristics of the systems and assemblies of vehicles requires the introduction of rational diagnosing testing. To reduce the cost of materials and ensure a rational resource of mated parts, as well as to reduce the number of service operations, a method is used to apply coatings onto the working surfaces of mated parts [32, 33]. A given procedure can be implemented at technical service only under the conditions of the overhaul of parts and after proving its effectiveness; that, however, requires significant capital investments in the service infrastructure of an enterprise.

The resource-defining mated parts of the diesel engines require studying their wear character [34], as well as diagnosing the preconditions of continuity [35]. The above enables obtaining sufficient information about the technical condition of the cylinder piston group; but it may additionally lead to the significant downtime of vehicles at technical service facilities, which is unacceptable. The most rational method of diagnosing a cylinder piston group is a compression method [36], which individually gives an incomplete picture of the local fault area, which can lead to low-quality service of the power unit of a vehicle. Operational reliability of the diesel engine is positively affected by various kinds of monitoring systems, which can timely detect the process of development of working defects in the power unit's systems [37]. These systems require constant training of service personnel, updating the firmware of microcontrollers, as well as structural interference in the design of diesel systems, which, at operation, is difficult to implement. It was found out that, for a small fleet of vehicles, monitoring systems are not economically feasible.

Therefore, the lack of detailed studies into the processes of diesel engine diagnosing, its resource-defining mated parts "sleeve-ring-piston" and "sleeve-piston", requires additional elucidation of patterns in the change in compression in the space above and over a piston depending on vehicle mileage. The development of information technologies and entropy approach to diagnosing information predetermine the intellectualization of service information with a possibility of its clarification in real exploitation and determining the significance of each diagnosing parameter of the technical condition of mated parts in the diesel engines. These issues are especially acute for a small fleet of trucks and the conditions of service operations at a minimum downtime. The above necessitates research into this area.

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### 3. The aim and objectives of the study

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The aim of this study is to build a system for determining the informativeness of diagnosing parameters of a cylinder piston group in the diesel engine KAMAZ-740.63-400 for the conditions of technical service rendered to trucks KAMAZ-6460, which would make it possible to improve their operational reliability.

To achieve the set aim, the following tasks have been solved:

- to determine the patterns of change in the compression indices of the space above a piston and the integrated compression-graphic indicator of the subcylindrical (crankcase) space in the diesel engine of trucks during operation;
- to define the vacuometric properties of a cylinder piston group;
- to establish, based on an entropy approach, the informativeness of diagnosing indices, which enable analyzing the level of information introduced in the service history of the trucks' diesel engines.

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### 4. Procedure for determining the informativeness of diagnosing parameters of a cylinder piston group during vehicle operation

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The diagnosing of the diesel engine is an important element in the technical maintenance since the timely detection of malfunctions improves the efficiency of vehicles and reduces the risks of sudden failure during exploitation. About 20 % of the operating cost of a truck accounts for the power unit. Much of the repair cost accounts for the mated parts within a cylinder piston group as a result of their wear. Diagnosing should involve a minimum level of disassembly; the downtime of vehicles should approach minimum duration. The analysis of diagnosing parameters was conducted in more detail, in order not to handle an overhaul without its real need, or not to miss the maximum permissible level of wear.

The cylinder-piston group connects to a crank mechanism and, in turn, provides for the tightness of cycles of the internal combustion engine. The important factors that influence the change in the technical condition of the diesel engine's cylinder piston group are significant pressures, as well as piston movements at reciprocating motion. The main diagnosing parameters that characterize the working characteristics of a cylindrical piston group are:

- the tightness of the space above a piston: the breakout of crankcase gases; compression properties; vacuometric properties;
- pneumatic-analytical;
- vibration;
- the composition of oil for the diesel engine's lubricating system, and others.

Of the most effective methods, among those above, we used the first group of diagnosing parameters. They maximally reflect the technical characteristics of the mated parts within a cylinder piston group. The study was performed at the logistics company ATP 2004, which is engaged in the transportation of agricultural products in the territory of Ukraine. Periodic control was carried out on the trucks Kamaz-6460, 5 vehicles, year of manufacture – 2012, the average annual mileage is  $45,000 \pm 3,000$  km, the third category of operating conditions, a mileage to overhaul is 40,000 km, maintenance No. 1 – 3,000 km, maintenance No. 2 – 12,000 km. These vehicles are equipped with the diesel engines KamAZ – 740.63-400 with the following characteristics: V8 configuration, power is 300 kW at 1,900 rpm, torque is 1,760 N·m. The frequency of control of the cylinder piston group was chosen based on the rated mileage, maintenance No. 2. The total number of parts in the investigated mated assembly: sleeves – 40 pcs., pistons – 40 pcs., compression rings – 80 pcs.

Diagnosing involved the measuring of a maximum pressure at the end of the compression stroke using the HS-A1019 compressor kit (HESHI TOOLS, PRC). The breakout of crankcase gases was controlled by the head meter NMP-52 (RF). The vacuometric properties of a cylinder piston group were measured using the vacuometric meter of the diesel engine pneumatic density (VMDP) (VICCO, RF). The overall view of the equipment is shown in Fig. 1.



Fig. 1. Equipment for determining the cylinder-piston group parameters: *a* – HS-A1019; *b* – NMP-52

We controlled the tightness of the cylinder piston group on a warmed-up diesel engine, whose temperature was not less than 60 °C. Rechargeable battery must be fully charged before the beginning of diagnosing. All measurements are carried out in pairs: one operator presses an accelerometer pedal and enables the ignition, and the other operator acquires the diagnosing indicators. Starter launch is required at every measurement over 3–5 s. The number of measurements is at least 3 times in each cylinder. The place of the measurement should not be dusty. Determining the maximum pressure at the end of the compression stroke should be carried out using a compressor meter in assembly with a hose and adapter, screwed into place of the removed atomizers of the diesel engine.

Compression indicators should not differ by more than 10–12 % because, during operation, this difference would cause uneven operation and increase the wear of parts within

a cylinder piston group and a crank group of the diesel engine. If the difference is greater than the specified norm, the diesel engine repair is required.

Measuring the breakout of crankcase gases with using the instrument (Fig. 1, *b*) NMP-52 should be performed with twisted nozzles on a warmed-up diesel engine. In the place of an oil measuring probe of the diesel engine, a rubber hose is pressed, connected to the instrument; over 7–10 s, control data are acquired. Before measuring, it is necessary to check the level of oil in the crankcase and, if necessary, bring it to normal. The hose of the instrument should be silicon-based as the material is softer and does not transmit vibration to the device. This, in turn, does not generate mechanical noise during measurements. The measurements were repeated at least three times on each diesel engine.

The vacuometric control of the properties of a cylinder piston group is possible by using a VMDP device. This device determines the values of a maximum vacuum, as well as the level of a residual vacuum. Measurements were carried out on a warmed-up diesel engine; VMDP is connected in the place of attachment of nozzles. Starter launch of the diesel engine diesel is necessary for 3–7 s at an open discharge valve of the device. After measuring, we pressed for 2 s the device's outlet valve button. On each cylinder, we repeated measurements at least three times. The measurement of a residual vacuum characterizes the amount of air transmission through the rings. With this method of measurement, the reduction valve must be closed completely. A procedure for measuring a residual vacuum is similar to the procedure of measuring a maximum vacuum.

Determining the information significance of the diagnosing parameters of a cylinder piston group is based on the use of an entropic approach that follows the fundamental principles of information theory. The implementation of a given approach based on the criterion of statistical informativeness makes it possible to select the informatively significant diagnosing parameters for a cylinder piston group or to take them into consideration according to the amount of information that they introduce in the service history of vehicles' assemblies.

The main stages in the informativeness of diagnosing information are the formation of technical states that the examined mated parts of the vehicles' systems and assemblies can enter. The first of them is serviceable, and all other technical states are defective, due to the failure or wear of certain elements in the resource-defining mated parts. All states are characterized by the magnitude of the probability of a failure-free operation. The defined diagnosing parameters and states of the mated parts in the systems and assemblies must be represented in the form of a matrix. Based on this matrix, we find the initial entropy of the examined mated parts of vehicles' systems and assemblies.

The informativeness of the diagnosing parameters is primarily characterized by the information entropy, which should be calculated for each parameter. Information entropy is an uncertainty in the studied mated parts when controlling its parameters. The next operation in the evaluation of a diagnosing parameter is to determine the amount of information acquired when controlling a diagnosing parameter. An algorithm of the proposed procedure of an entropic approach to estimating the informative significance of the



diagnosing parameters of mated parts in vehicles' assemblies is schematically shown in Fig. 2.

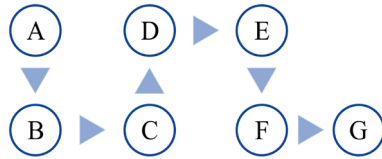


Fig. 2. Schematic of an algorithm of the system for determining the informatively significant diagnosing parameters of the technical condition of the examined mated parts of vehicles: A, B, C, D, E, F, G – units in the entropic approach procedure

The beginning of the scheme shows unit A, which characterizes the formation of a rational list of the diagnosing parameters that must be controlled in the examined mated parts of vehicles' systems and assemblies. In turn, unit B is responsible for defining the possible technical states of the studied mated parts. Unit C enables forming a technical state matrix of the examined mated parts. The rows of the matrix characterize the diagnosing parameters, the columns – possible states. At the intersection of the columns and rows in the matrix, we enter value 0, when finding a diagnosing parameter within the permissible limits, and 1 – otherwise. The next unit D calculates the indicators of a resource, the intensity of failure, the probability of a failure-free operation of each state of the studied mated parts in the power unit of a vehicle and the probability of failure occurrence:

$$l_{sr} = \sum_{i=1}^I \bar{l}_i n_i(\Delta l), \tag{1}$$

$$\lambda(s_j(\Delta l)) = 1 - \frac{n(\Delta l)}{(N_0 - n(\Delta l)) \cdot l_{sr}}, \tag{2}$$

$$P(s_j(\Delta l)) = \exp(-\lambda(s_j(\Delta l)) \cdot \Delta l), \tag{3}$$

$$F(s_j(\Delta l)) = 1 - P(s_j(\Delta l)), \tag{4}$$

where  $n_i(\Delta l)$  are the faults in the  $i$ -th mileage interval;  $\bar{l}_i$  is the middle of the  $i$ -th work interval;  $n(\Delta l)$  is the number of failures, which characterize the condition of a cylinder piston group in the interval of a vehicle's mileage;  $N_0$  is the total number of the examined parts that reflects one mating state;  $\Delta l$  is the operation duration of a vehicle;  $l_{sr}$  is the accumulated wear during exploitation.

In unit E, it is necessary to calculate information entropy indicators for each diagnosing parameter of mated parts in the vehicles' systems and assemblies, taking into consideration the detected conditions in the technical operation:

$$H_i(D_i) = -\sum_{j=0}^S P(s_j) \log_2 P(s_j), \tag{5}$$

where  $P(s_j)$  is the probability of a serviceable state, determined by the probability of the occurrence of a corresponding malfunction;  $S$  is the total number of states.

Unit F determines the amount of information obtained in the control of each diagnosing parameter:

$$I_{D_i} = |H_0 - H_i(D_i)|, \tag{6}$$

where  $H_0$  is the a priori entropy of mated parts in a cylinder piston group, relative to the reliability of this mating type during exploitation.

The final unit G chooses the diagnosing parameters according to the criterion of statistical informativeness. If a relative difference in the magnitude of the starting entropy and each diagnosing parameter is more than 80 %, then the corresponding diagnosing parameter can be ignored. Or it is necessary to devise the recommendations for a service department that it is necessary, when forecasting the technical condition based on the examined diagnosing parameter, to take into consideration the weight coefficient according to the diagnosing informativeness.

The proposed methodology proves that it is possible, based on the entropy approach and the application of information theory methods, to assess both the number of diagnosing parameters and their informativeness. In this case, the reliability of determining the technical condition of the studied mated parts of vehicles' systems and assemblies is not compromised. It was discovered that the estimated diagnosing parameters are easier to consider when forecasting a state function under conditions of real operation.

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## 5. Results of studying the informativeness of the diagnosing parameters of a cylinder piston group in the operation of trucks

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### 5.1. Determining values for the diagnosing parameters of a cylinder-piston group in the examined diesel engines based on the compression and vacuometric indicators

We investigated the technical condition of a cylinder piston group in 2018–2019. Since the technical condition was checked periodically, with the requirement to register the trucks downtime, we decided that the period of control was to coincide with maintenance No. 2. General mileage for data collection was 60,000 km; this period makes it possible to track the trend of changes in the diagnosing parameters during technical exploitation.

We determined and controlled the pressure of gases that burst into the diesel engine crankcase using the device NMP-52, according to the corresponding procedure for diagnosing a given parameter. The rated crankcase gas pressure is 0.7–0.75 KPa, this pressure corresponds to an absolutely proper state of the diesel engine's cylinder piston group. The threshold of a crankcase gas pressure is within 2.39–2.41 KPa and mainly characterizes the integrated wear of the diesel engine's compression rings and piston.

The results of the obtained values from diagnosing the breakout of the diesel engine's crankcase gases during periodic control are shown in Fig. 3; the values beyond the permissible limits are shown in red.

We determined compression in the diesel engine's cylinders at each maintenance No. 2 on a warmed-up engine. The difference in cylinders in the diesel engine of each vehicle should not exceed 10–12 % or compression should not be less than 3.05 MPa. The average compression value of a cylinder piston group and the percentage of the difference between the maximal and minimum compression value in a cylinder piston group of each cylinder in the examined vehicles is shown in Fig. 3. The values beyond the permissible limits are shown in red.

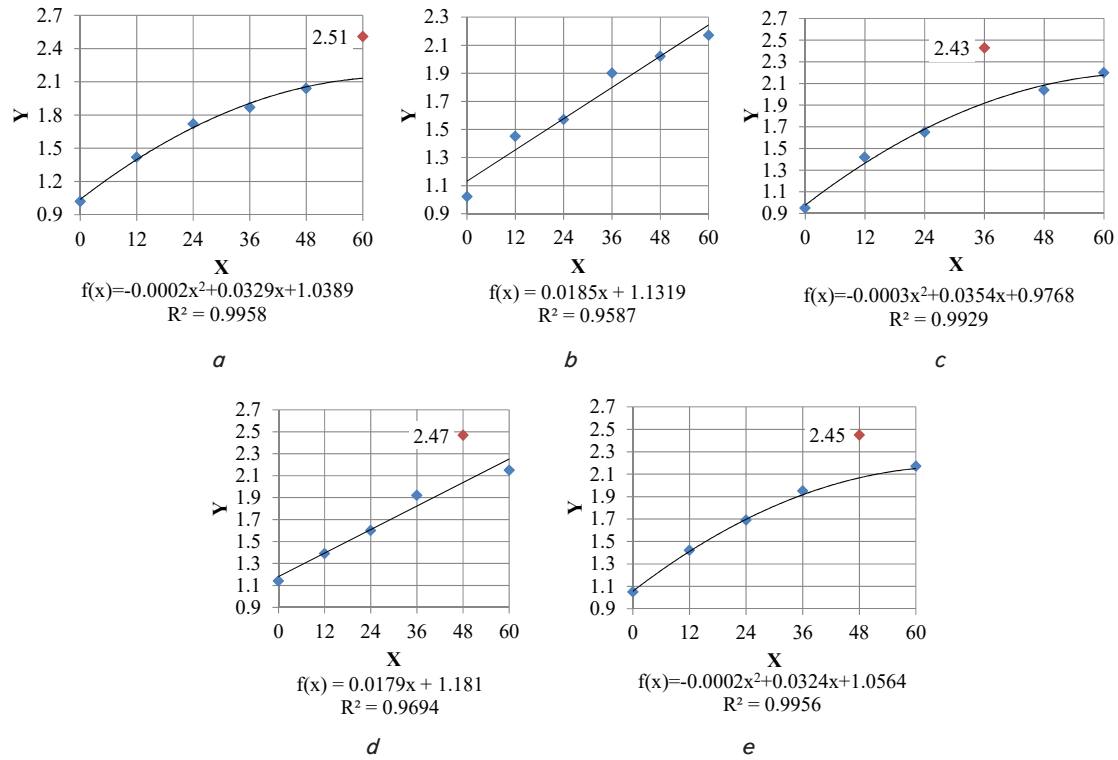


Fig. 3. Average values of the diesel engine's crankcase gas pressure during the examined operation: Y – the average crankcase gas pressure, KPa; X – vehicle mileage, thousand km; a – truck No. 1, b – truck No. 2, c – truck No. 3, d – truck No. 4, e – truck No. 5

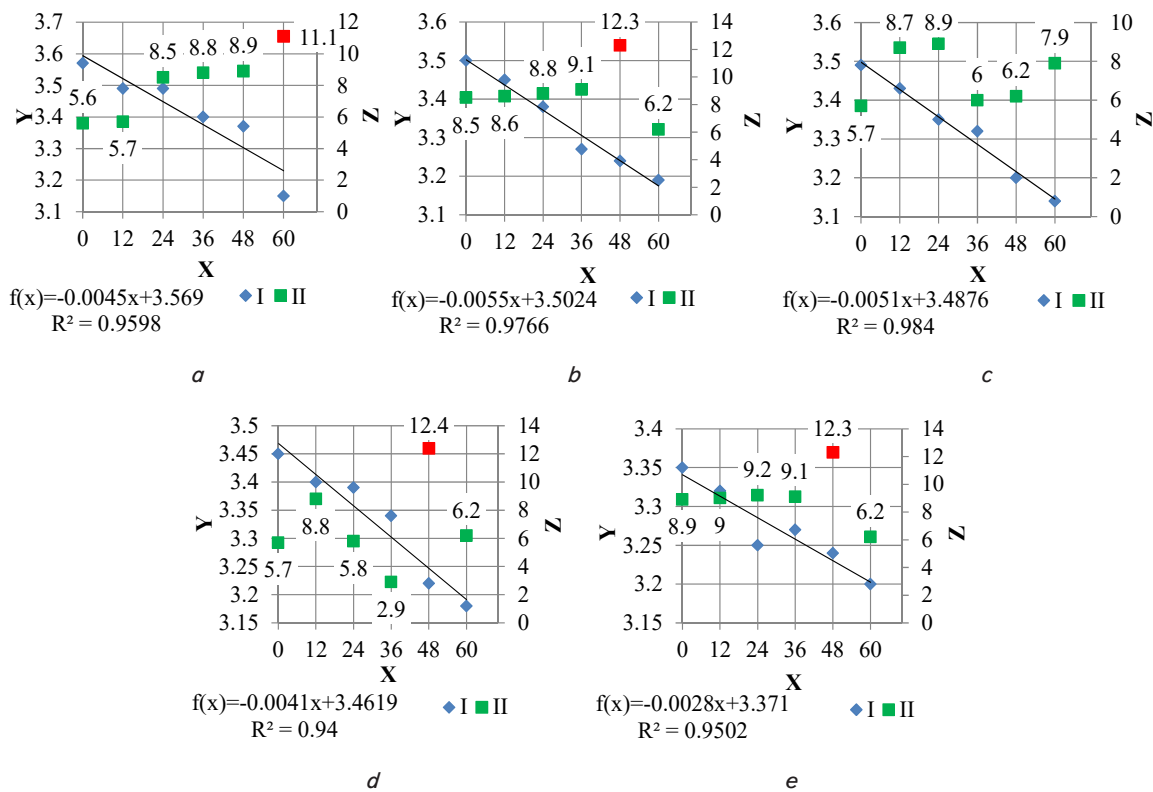


Fig. 4. The average values of compression and difference, in the percentage, in the diesel engine's cylinder piston group during the examined operation: Y – average value of compression in the diesel engine's cylinders, MPa; X – vehicle mileage, thousand km; Z – a maximum magnitude of the compression difference in the diesel engine's cylinders, %; a – truck No. 1; b – truck No. 2; c – truck No. 3; d – truck No. 4; e – truck No. 5; I – compression indicators; II – indicators of compression difference in cylinders

We determined the vacuometric indicators for cylinders using the VMDP equipment and the corresponding diagnosing procedure. Based on these diagnosing parameters, we determined the maximum  $P_m$  and residual  $P_z$  vacuum magnitude. The wear of the cylinder piston-groups of the examined diesel engines based on the vacuometric indices is described by an  $P_m$  value: lower, 69 KPa, upper, 86 KPa; for  $P_z$ : lower, 26 KPa, upper, 41 KPa. Average values of the vacuometric indicators of the examined diesel engines during their technical exploitation are shown in Fig. 4.

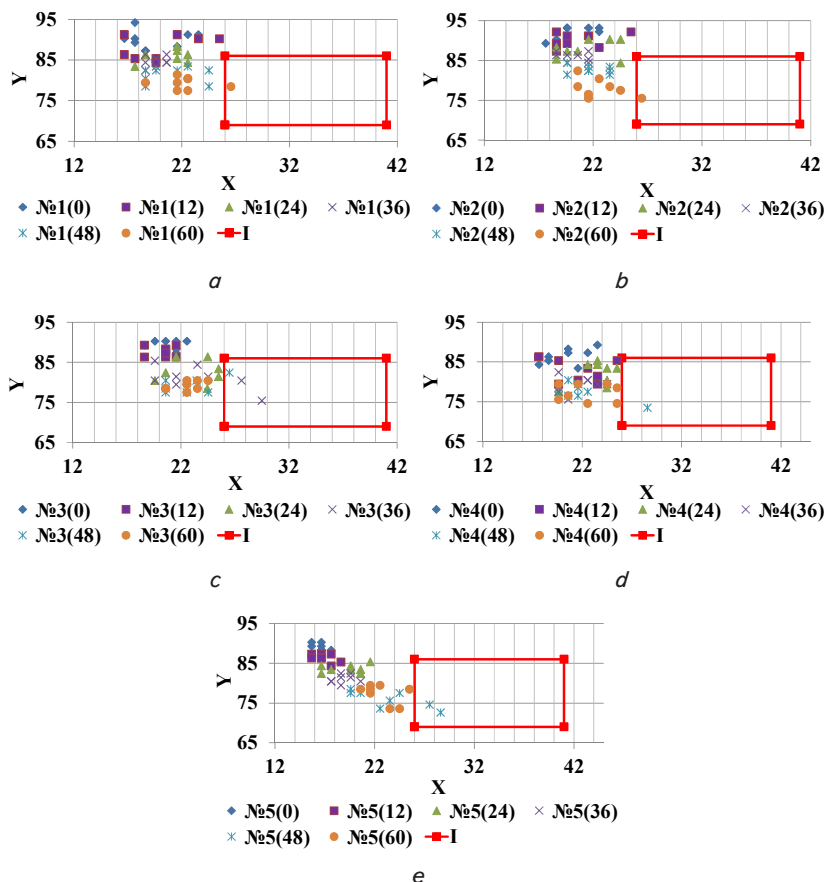


Fig. 5. Average values of the vacuometric indicators for the diagnosing parameters of the examined vehicles' diesel engines during their technical exploitation: Y – average value of a maximum vacuum  $P_m$ , KPa; X – average value of a residual vacuum  $P_z$ , KPa; I – a zone describing the threshold of wear; a – truck No. 1; b – truck No. 2; c – truck No. 3; d – truck No. 4; e – truck No. 5; I – a zone of critical wear of parts in a cylinder piston group

After determining the values of the diagnosing parameters, it is necessary to implement an entropy approach to assess the informality of the studied diagnosing parameters.

### 5. 2. Determining the informativeness of the diagnosing parameters for a cylinder piston group when using an entropic approach

Based on the study results, we determine the informativeness of the diagnosing parameters of a cylinder piston group of the trucks' diesel engines according to the algorithm, schematically shown in Fig. 2.

In the initial stage of compiling a list of the diagnosing parameters for power units, we defined the system of parameters for the diesel engine's technical condition to be

diagnosed, followed by the calculations of the informative significance of each controlled parameter. To this end, the structural and consequential methods for the diagnosed object are used.

Constraints on the choice of the diagnosing parameters were the availability of equipment, organizational maintenance at an enterprise; the integrated character of the selected diagnosing indicators. A matrix of states characterizing the recognition of the diagnosing parameters was constructed.

A cylinder piston group of the diesel engine can enter both serviceable and defective technical states, due to the wear of mated parts. Each condition is characterized by the probability of the occurrence of wear signs. The probability of a serviceable state is defined as the probability of an opposite event.

Considering a probability addition theorem, the probability of the occurrence of one of several independent and incompatible similar events equals the sum of the probabilities of these events. The probability  $P(\bar{S}_0)$  is taken equal to the sum of the probabilities of failure by the constituent elements of the diagnosed object. As a result, by ignoring the probability of the occurrence of the totality of failures ( $S_1, \dots, S_j$ ), we accepted the occurrence of these events as independent. The probability of the possible states of a cylinder piston group of the diesel engine was determined taking into consideration the probability of failure and the failure ratio over mileage intervals.

Consider the technical conditions of a cylinder piston group of the diesel engine based on the matrix of technical states of the cylinder piston group (Table 1), which includes the proper technical condition  $S_0$  and the defective technical conditions of mated parts. Failures are characterized by the following reasons: the wear of a cylinder sleeve –  $S_1$ ; the wear of a piston –  $S_2$ ; the wear of compression rings –  $S_3$ , as well as those diagnosing parameters that reflect the maximum fault of the mated parts.

Table 1

Matrix of the technical conditions of a cylinder piston group of the examined trucks' diesel engines

| Parameter                        | Technical condition |       |       |       |
|----------------------------------|---------------------|-------|-------|-------|
|                                  | $S_0$               | $S_1$ | $S_2$ | $S_3$ |
| $D_1$ – crankcase gas pressure   | 0                   | 0     | 1     | 1     |
| $D_2$ – compression in cylinders | 0                   | 1     | 0     | 1     |
| $D_3$ – vacuometric indicators   | 0                   | 1     | 1     | 1     |

We examined five trucks KamAZ-6460 from the logistics enterprise ATP 2004. The characteristics of the reliability of the cylinder-piston group's parts were calculated according to appropriate formulae (1) to (4). The technical conditions of the cylinders' sleeves, pistons, and rings of the

diesel engine are given in Tables 2–4 based on the reliability indicators.

Table 2

Values of reliability indicators of the technical state of the cylinders' sleeves in the examined trucks

| Mileage, thousand km | Failure quantity | Failure rate           | Part's reliability | Failure probability |
|----------------------|------------------|------------------------|--------------------|---------------------|
| 0...12               | 0                | 1.097×10 <sup>-6</sup> | 0.936              | 0.064               |
| 12...24              | 0                |                        |                    |                     |
| 24...36              | 0                |                        |                    |                     |
| 36...48              | 1                |                        |                    |                     |
| 48...60              | 1                |                        |                    |                     |

Data from Table 2 show that for the cylinders' sleeves of the examined diesel engine, over the experimental mileage interval, the maximum failure intensity is within the interval of 36,000...60,000 km. At the same time, the onset of the limit wear for some sleeves starts within the mileage interval of 36,000...48,000 km. A significant decrease in the resource of the vehicles' cylinder sleeves during operation is caused by tough operating conditions, the presence of overloads, and the insufficient quality of organizational technical service.

Table 3

Values of reliability indicators for the technical condition of the examined trucks' diesel engines pistons

| Mileage, thousand km | Failure quantity | Failure rate          | Part's reliability | Failure probability |
|----------------------|------------------|-----------------------|--------------------|---------------------|
| 0...12               | 0                | 1.76×10 <sup>-6</sup> | 0.899              | 0.101               |
| 12...24              | 0                |                       |                    |                     |
| 24...36              | 0                |                       |                    |                     |
| 36...48              | 2                |                       |                    |                     |
| 48...60              | 1                |                       |                    |                     |

One can see that for the pistons in the diesel engines of trucks from the KamAZ family, over the examined interval of operation, the maximum number of piston failures is observed in the mileage interval of 36,000...60,000 km.

Table 4

Values of reliability indicators for the technical condition of compression rings in the diesel engines of the examined trucks

| Mileage, thousand km | Failure quantity | Failure rate          | Part's reliability | Failure probability |
|----------------------|------------------|-----------------------|--------------------|---------------------|
| 0...12               | 0                | 1.25×10 <sup>-6</sup> | 0.928              | 0.072               |
| 12...24              | 0                |                       |                    |                     |
| 24...36              | 0                |                       |                    |                     |
| 36...48              | 4                |                       |                    |                     |
| 48...60              | 0                |                       |                    |                     |

Data from Table 4 testify that for the compression rings of a truck's diesel engine the maximum number of failures is within the operation interval of 36,000...48,000 km.

The probability of the initial state was determined based on the principle of consistently connected mated parts. The following conditions of the cylinder-piston group, according to reliability indices, were calculated from formula (4) based on exponential distribution, given in Table 5.

Table 5

Values of average probability of the technical conditions of the diesel engine's cylinder-piston group

| Technical conditions of the diesel engine's cylinder-piston group | The average probability of technical condition at a mileage of 60.000 km |
|---|--|
| S <sub>0</sub> – serviceable state                                | 0.278  |
| S <sub>1</sub> – the wear of the cylinders' sleeve                | 0.253  |
| S <sub>2</sub> – the wear of a piston                             | 0.333  |
| S <sub>3</sub> – the wear of the rings                            | 0.274  |

By using these data, it is possible to derive values for the information entropy indicators (5), the diagnosing parameters for the technical conditions of a cylinder piston group reflected in the matrix, and the amount of information (6), which is introduced by each diagnosing parameter (Table 6). According to Table 1, we calculate the informativeness of the diagnosing parameters.

Table 6

Values of informativeness of the diagnosing parameters of a cylinder piston group

| Diagnosing parameter                      | Entropy after diagnosing | Informative significance |
|---|--------------------------|--------------------------|
| D <sub>1</sub> – crankcase gas pressure   | 0.607                    | 0.329                    |
| D <sub>2</sub> – compression in cylinders | 0.527                    | 0.249                    |
| D <sub>3</sub> – vacuometric indicators   | 0.86                     | 0.582                    |

It should be noted that the calculations for determining the informatively significant diagnosing parameters were conducted on a personal computer using the MS Excel or MS Access software.

### 6. Discussion of the study results and analysis of diagnosing the technical condition of the diesel engine's cylinder piston group

In the course of our study into diagnosing a cylinder-piston group during technical exploitation of the diesel engines at the enterprise ATP-2004, we determined the characteristic signs of the wear of components in the examined mated parts. In turn, Fig. 3 shows how a crankcase gas pressure varies during the run of the truck KamAZ-6460. Leaving the permissible limits of crankcase gas pressure during operation is characterized by the wear of compression rings and pistons, namely, their sleeve and grooves for rings. The proposed type of diagnosing is very effective for integrated diagnosing because it characterizes the general condition of all cylinder piston groups of the diesel engine. In addition, a given diagnosing method is rational because it has low labor intensity, up to 0.5 hour of service taking into consideration the preparatory operations. However, the shortcomings of a given method are the impossibility to localize a fault site since it does not produce values for individual cylinder-piston groups. Fig. 3 shows at which stage of exploitation the technical condition of the examined mated parts reaches beyond the norm of tolerance for commercial vehicles: No. 1 (60,000 km.), No. 3 (36,000 km.), No. 4 (48,000 km), No. 5 (48,000 km). At different mileage, it is necessary to carry out additional diagnosing operations. If one does not



consider the proposed method at diagnosing, it is possible to skip the period of an increase in the amount of crankcase gases that are in contact with the motor oil. Such a contact causes the oxidation of a motor oil, the result could be the larger wear, by 12–18 %, of other parts of the diesel engine.

An important characteristic in the technical exploitation of the diesel engine is the uniformity of its operation in each cylinder. Uneven operation of the diesel engine leads to an increase in its operational cost. The consequence is the inefficiency of the truck as a logistics element. The uneven operation of the diesel engine's cylinders increases by more than 10 % the occurrence of sleeve fraying, the wear of root and crank necks of the crankshaft, as well as their liners. This is primarily due to the uneven inertia forces of the diesel engine. Therefore, compression control in the diesel engine's cylinders makes it possible to analyze the evenness of the work of the diesel engine's parts in a truck, as well as to assess the wear level of the cylinder sleeve and compression rings. Fig. 4 shows the obvious signs of the uneven operation of the trucks' diesel engines on the runs: No. 1 – 60,000 km, No. 2 – 48,000 km, No. 4 – 48,000 km, No. 5 – 48,000 km. Under these conditions, it is necessary to replace the parts of the diesel engine, as well as to align their operation so that the diagnosing parameters come to normal or to use additives to the motor oil to reduce the unused resource before the diesel engine overhaul.

This study requires the knowledge of the starting working characteristics of a cylinder piston group of the truck's diesel engine as these data are responsible for the preparation of a working fuel-air mixture. Improperly prepared fuel and air mixture causes the uneven operation of the diesel engine, the formation of improper working temperature mode of the diesel engine, as well as the wear of cylinders, compression rings, and pistons. Insufficient vacuum indicators increase the smoke of exhaust gases by charring the particles of fuel and their incomplete combustion. The reduction of vacuum indicators increases the carbon deposits on parts and thus reduces the heat exchange processes that results in the change in the geometric dimensions of components in the diesel engine operation. Changing the geometric dimensions of parts in the diesel engine affects the wear intensity of a cylinder piston group.

Control over the vacuum indicators is illustrated in Fig. 5. The boundary wear area, based on this diagnosing parameter, is outlined as a rectangle. This region was detected during the technical maintenance regarding the service history of the diesel engines KamAZ-740.63-400. According to a given method of diagnosing, it is convenient to analyze the state of work for each cylinder. When a value of the diagnosing parameters for any cylinder enters the boundary wear area, it is possible to assert the malfunction of the cylinder piston group. We have determined the characteristic runs of trucks and faults at the same time: No. 1 – 60,000 km, a cylinder-piston group I failure; No. 2 – 60,000 km, a cylinder-piston group I failure; No. 3 – 36,000 km, a cylinder-piston group 2 failure; No. 3 – 48,000 km, a cylinder-piston group I failure; No. 4 – 48,000 km, a cylinder-piston group I failure; No. 5 – 48,000 km, a cylinder-piston group 2 failure. Replacing the respective parts and the alignment of their mated parts make it possible to prolong the diesel engine resource.

Our study of the diagnosing parameters using an entropy approach has determined their real weight values in the operation of trucks. The informative significance

of the diagnosing parameters of the technical condition of a cylinder-piston group in the KamAZ-6460 trucks was determined: a crankcase gas pressure  $D_1$  – 0.329 bits; compression in the cylinders  $D_2$  – 0.249 bits; vacuum indicators  $D_3$  – 0.582 bits. Their relative percentage characteristics are:  $D_1$  – 28 %,  $D_2$  – 22 %,  $D_3$  – 50 %. It was established that reducing the cost of diagnosing makes it possible to realize compositions consisting of the incomplete number of the diagnosing parameters  $D_1+D_3$  and  $D_2+D_3$ . The most accurate composition of the studied diagnosing parameters is  $D_1+D_2+D_3$ , for determining the faults in a cylinder piston group, and from the economic point of view –  $D_1+D_3$ .

An important limitation when implementing a given method is constant control and documenting of service history about the technical condition of the diesel engine's cylinder-piston group. For different diesel engines, it is necessary to determine and adjust the runs in accordance with the relevant maintenance time and diagnosing. In addition, diagnosing implies the application of technically serviceable diagnosing equipment and the involvement of well-informed technical personnel. It is important to determine the informativeness of diagnosing parameters and to implement an entropy approach employing analytical software. This, in turn, could reduce the time for engineering calculations, and would also help expand the possibility of forecasting the technical condition of the examined mated parts. The easiest to implement is the Excel software environment. For industrial use, given a significant number of vehicles and control mated parts, it is advisable to use the software Access MS, which has more automation tools.

Further research in this area requires the detection of the rules for localizing the sites of defects or the wear of parts in a cylinder piston group. Our study is useful for the engineering industry, namely, technical exploitation of trucks and transport machines. The devised procedures could be implemented at service departments of transportation companies or service enterprises, in order to align the resource of a cylinder piston group in the diesel engines at minimum capital costs.

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## 7. Conclusions

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1. We have determined patterns in diagnosing a cylinder piston group while implementing an entropic approach to diagnosing information. Based on the compression and vacuum indicators, we established regularities in a change of crankcase gas pressure  $D_1$  and a change in the average compression value  $D_2$  during technical exploitation of trucks KamAZ 6460. The signs and norms of failure in a cylinder-piston group's parts based on the diagnosing parameters were defined:  $D_1$  – 2.39–2.41 KPa;  $D_2$  – the difference between cylinders is 10–12 %. For the vacuum indicators  $D_3$ , the failure of parts is characterized by the following boundaries: a maximum vacuum value, 69–86 KPa, residual vacuum, 26–41 KPa, respectively, for the family of trucks KamAZ-6460.

2. Based on data from the vacuum method of diagnosing a cylinder piston group, it is convenient to analyze the state of work for each cylinder. When a value of the diagnosing parameters for any cylinder enters the boundary wear area, it is possible to assert the malfunction of a cylinder piston group. We have determined the

characteristic runs of trucks and faults at the same time:  
 No. 1 – 60,000 km, a failure of 1 cylinder piston group;  
 No. 2 – 60,000 km, a failure of 1 cylinder piston group;  
 No. 3 – 3,6000 km, a failure of 2 cylinder-piston group;  
 No. 3 – 48,000 km, a failure of 1 cylinder piston group;  
 No. 4 – 48,000 km, a failure of 1 cylinder piston group;  
 No. 5 – 48,000 km, a failure of 2 cylinder piston group. It has been found out that in these operation intervals it is necessary to carry out additional repair operations or use composite motor oils with tribological additives.

3. An analysis of the informativeness of the diagnosing parameters based on an entropic approach makes it possible to assess the rational use of diagnosing. Our study has established that diagnosing the parameter  $D_1$  introduces 0.329 bits of information on the technical condition of a cylinder piston group,  $D_2$  – 0.249 bits,  $D_3$  – 0.582 bits. Knowing the levels of the informativeness of the diagnosing parameters makes it possible to realize the rational determination of the technical condition while considering them when forecasting a technical state.

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