Proposals for reduction of the cost of ownership of agricultural machinery due to increase controllability and adaptability to diagnosis

Mikhail Kostomakhin1*, Nikolay Kostomakhin2, Yury Kataev1 Nikolay Petrishchev1, and Mikhail Tseiko3

1Federal Scientific Agro-Engineering Center VIM, 1 Institutsky proezd, 5, Moscow, 109428, Russia
2Russian State Agrarian University – Moscow Timiryazev Agricultural Academy, Timiryazevskaya str., 49, 127550, Moscow, Russia
3Kaliningrad Research Institute of Agriculture, All-Russian Research Institute of Phytopathology (5 Institute Str., 143050, Bolshie Vyazemy, Odintsovsky district, Moscow region, Russia

Abstract. It is known that machinery in agriculture is used to perform work in optimal agricultural terms under difficult conditions, which requires constant improvement of approaches to determining the technical condition. Technical service is the main and most effective measure that ensures the maintenance of machines in working condition during the life cycle. At the same time, in order to objectively determine the technical condition of the machine, it is necessary to obtain an appropriate amount of data reliably describing this condition. Obtaining such data in the required volume will reduce the total cost of ownership and preserve the consumer properties of machines throughout the life cycle. As a result of the carried out research within the framework of the scientific topic "To develop a system of digital monitoring and diagnostics of the technical condition of agricultural machinery", projects were proposed to improve the controllability and adaptability to diagnostics to improve consumer qualities during the life cycle. The draft proposals are based on an analysis of the failure criteria for the complexity group, the existing Standards and Technical Documentation, as well as the capabilities of equipment manufacturers to carry out measures to manage reliability during the warranty and post-warranty periods of the life cycle equipment. During the study, special attention was paid to the possibilities of conducting non-selective diagnostics of components and assemblies using Predictive Maintenance Systems (PdM) to preserve the consumer properties of equipment.

1 Introduction

Currently, according to the Decree of the Government of the Russian Federation No. 740 dated 01.08.2016, there is a list of criteria for determining the functional characteristics

* Corresponding author: redizdat@mail.ru
(consumer properties) and efficiency of agricultural machinery, on the basis of which the user properties of machinery are evaluated at the Machine Testing Station [1].

Since the purchased agricultural machinery (as the goods) has certain functional characteristics (consumer properties), their control is necessary to ensure compliance with the performance of work in optimal agricultural terms in order to obtain the planned economic effect. The use of a set of diagnostic measures provides a significant economic benefit, consisting in increasing the operating time for a complex failure and minimizing excess costs, which is possible by increasing the controllability of the units of manufactured equipment and constantly improving diagnostic tools.

Purpose of research to analyze the Standards and Technical Documentation for the development of proposals for the preservation of consumer properties and efficiency of agricultural machinery during the life cycle (LC) based on the improvement of diagnostic tools and controllability of aggregates.

2 Materials and methods


It is known that in order to preserve the consumer qualities of agricultural machinery during the LC, three main strategies of repair and maintenance work are used (C1, C2, C3). For example, at C1 repair effects are carried out according to need after failures occur to eliminate their consequences; when C2 they effect cyclically according to the regulations based on operating time (according to State Standard 20793—2009 [3]); when C3 the y are according to the actual condition determined by diagnostics, the indication of on-board continuous monitoring systems. In the practical implementation of various strategies, the failure rate of the component changes during the life cycle: for strategy C1 it is 100%, C2 it is up to 9%, C3 it is up to 3%, respectively [4, 5].

In this case, minimizing the failure rate will characterize better consumer properties of the product and, in this case the C3 strategy should be used to improve consumer qualities.

The analysis of approaches in the classification of failure characteristics by complexity groups determined during the control of the technical condition of agricultural machinery has shown that most of the methods and means used to determine them need improvement. First of all, improvement is necessary to increase the level of controllability and adaptability of units, aggregates to diagnostics in order to preserve the consumer qualities of equipment and reduce the total cost of ownership.

3 Results and discussion

In order to comply with the Decree of the Government of the Russian Federation No. 740 of 01.08.2016, when assessing the consumer properties of tractors and self-propelled agricultural machines during tests, special attention is paid to monitoring the failure time of the II and III groups of complexity. For example, for wheeled tractors the corresponding operating time for failure should be at least 400-500 cumulative hours of engine running,
and for forage harvesters, grain harvesters it is at least 150 and 100 cumulative hours of engine running [1].

At the same time, the time to failure by complexity groups, in turn is a generalized indicator of the degree of perfection and reliability of the design, compliance with the rules of operation and reliability-oriented maintenance. Reliability indicators depend significantly on the maintenance strategies used, as well as on the indicator of controllability and adaptability to the diagnosis of individual components and aggregates.

The information in most cases is obtained during the diagnosis of equipment after repair or during routine maintenance according to National State Standard 20793-2009 [3], which is carried out according to the developments (strategy C2). The information obtained gives an idea to the owner of the equipment about the compliance of the technical condition and consumer properties of individual systems with a significant delay, characterized by the time of diagnosis or detection of inconsistencies during operation. This, in turn can lead to the increase in the spread of the consequences of failure, increases its group and significantly increases the cost of elimination, which requires the development of proposals for modern means of assessing the technical condition.

There are several interpretations of classifications by failure complexity groups (Table 1), which from the point of view of assessing consumer properties, leads to a misunderstanding by the owner of their real complexity and the costs of their elimination, since the characteristics of failure groups by complexity are based on either taking into account the time of elimination or the need for additional maintenance and routine repairs, but at the same time they are not characterized by the level of possible maintenance and repair costs, including diagnostics to identify a group of failures [6-9].

<table>
<thead>
<tr>
<th>Failure Group</th>
<th>Definition</th>
<th>State Standard 27434-87</th>
<th>State Scientific and Research Institute of Repair and Maintenance Tractors and Agricultural Machinery</th>
<th>Scientific and Research Auto and Tractor Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Failures of easily accessible parts and assembly units eliminated by replacing them or eliminated without removing the failed parts and assembly units from the tractor. The operational duration of the elimination of the failure of the first group of complexity should be no more than 2 hours.</td>
<td>Failures that can be eliminated by repairing or replacing parts located outside of assemblies and assemblies without disassembling them, as well as failures whose elimination requires extraordinary operations maintenance-1 and maintenance-2.</td>
<td>Failures are insignificant (insignificant) with a downtime of less than 1 hour, to eliminate which a standard tool and universal pullers are used.</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Failures of parts and assembly units, eliminated by repair, requiring the disclosure of internal cavities of assembly units. At the same time, the operational duration of the elimination of the failure should be no more than 8 hours.</td>
<td>Failures that can be eliminated by repairing or replacing easily accessible components and assemblies, as well as those whose elimination requires the disclosure of the internal cavities of the main units without disassembling them or extraordinary maintenance-2 operations.</td>
<td>Significant failures with a downtime of up to 5 hours, which are eliminated with using a mechanic's kit, universal equipment, welding machine.</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Failures with an operational duration of elimination of which is more than 8 hours.</td>
<td>Failures eliminated by disassembly of the main units.</td>
<td>The failure is severe, with an idle time of more than 5 hours, to eliminate which with special equipment, control and test benches are used.</td>
<td></td>
</tr>
</tbody>
</table>

It should be noted that when assessing the consumer properties of equipment, they are not taken into account:
- the possibilities of using various methods of restoring a product after failure such as replacement of a component part, replacement of an assembly unit, repair of an assembly unit by replacement of a part, repair of an assembly unit by restoration of a part, adjustment [10];
- failures of the I group of complexity, which taking into account the parameters of technical and environmental safety, prohibit the operation of equipment [11];
- categories of severity of the consequences of failures [12] (table 2);
- availability in the operating instructions of the approved nomenclature of control and diagnostic service equipment for assessing the technical condition and carrying out maintenance work, as well as resource diagnostics [3, 13];
- the presence of built-in systems for detecting failures, determining their criticality and localization of malfunctions in the form of a coefficient of repair-in-place diagnosis (Cr.d.) [14, 15].

Table 2. Categories of severity of the consequences of failures

<table>
<thead>
<tr>
<th>Category of severity of the consequences of failures</th>
<th>Characteristics of the severity of the consequences of failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>Failure, which can quickly and with high probability lead to significant damage to the object itself and/or the environment, death or serious injury to people, disruption of the task</td>
</tr>
<tr>
<td>III</td>
<td>Failure, which can quickly and with high probability cause significant damage to the object itself and/or the environment, disruption of the task being performed, but creates a negligible threat to human life and health</td>
</tr>
<tr>
<td>II</td>
<td>Failure, which may delay the task, reduce the readiness and efficiency of the facility, but does not pose a danger to the environment, the facility itself and human health</td>
</tr>
<tr>
<td>I</td>
<td>Failure, which may lead to a decrease in the quality of the functioning of the facility, but does not pose a danger to the environment, the facility itself and human health</td>
</tr>
</tbody>
</table>

A feature of the operation of agricultural machinery is the logistical distance from service centers, therefore in order to ensure a high availability coefficient (Ca) at the level of 0.98 [1], continuous improvement of the product in terms of reliability indicators is necessary to ensure consumer properties during the warranty period and after the warranty period of life cycle. Violation of agricultural contracts carries significant risks of reducing yields and increasing the cost of production, which in turn negatively affects the level of profit of agricultural enterprises. In many ways, violations of agricultural practices occur due to equipment failures, as well as the time spent on their elimination. Accordingly, the consumer of technology is interested in high consumer properties as a tool for making a profit.

According to our opinion, in order to determine the consumer properties of machinery during the LC, agricultural machinery manufacturers need to indicate not only the generalized level of operating costs and the recommended cost of maintenance for engine running time, but also to determine the range of operating costs for various types of work (transport, agricultural, industrial). Also, the cost of eliminating the consequences of failures of components and assemblies, especially in the post-warranty period of the LC, may vary depending on the season and the urgency of service work. A flexible tool for accounting for these costs would allow consumers of products to optimize the cost of
ownership of products, and dealer’s services to fulfill the volume of obligations, taking into account the customer's plans to prepare equipment for work.

At the same time, the level of costs to cover the costs of maintaining equipment in working condition should be adequate from the point of view of the cost of ownership, and should be based on the selection criteria in the form of technical characteristics and their preservation during the LC for the implementation of the business plan for which the equipment is purchased in fact.

Manufacturers based on their own data develop techniques for the total cost of equipment with an indication of the cost of ownership for car owners, which allows us to give some idea to a potential consumer of the product about the possible level of costs, taking into account the nomenclature of manufactured equipment, as well as the cost of branded technical services [16, 17]. These techniques are widely used by high-tech and high-performance consumer customers to plan and control their costs. In general, the total cost of ownership (TCO) can be represented as a formula:

\[
TCO = A + (E \times n), \text{rub}
\]

- A – capital (purchase price) costs, RUB;
- E – operating costs, RUB;
- n – the number of planned years of operation, years.

For example, AO "Petersburg Tractor Plant" for potential consumers cites (in 2015 prices) the following cost items during the operation of the "Kirovets" tractor for comparison with an analog of foreign production (Table 3) [18].

According to predictions for 2023 the ratio of expenses for repair and maintenance of foreign-made equipment by analogy with cars, may change significantly (by 1.5...3.5 times) including due to the risks of violation of delivery dates to dealers of spare parts, components, consumables, which in turn will negatively affect compliance agricultural terms.

**Table 3. Example of comparison of operating costs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tractor manufactured in the USA</th>
<th>&quot;Kirovets&quot; K-744P1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repair costs, RUB/cum. hours</td>
<td>752</td>
<td>245</td>
</tr>
<tr>
<td>The cost of automotive maintenance, RUB/cum. hours</td>
<td>131</td>
<td>52</td>
</tr>
<tr>
<td>Fuel costs, RUB/cum. hours</td>
<td>1750</td>
<td>1995</td>
</tr>
<tr>
<td>The price of a new tractor, RUB</td>
<td>14 260 000</td>
<td>5 451 600</td>
</tr>
<tr>
<td>The price of a tractor on the secondary market, RUB</td>
<td>5 300 000</td>
<td>2 200 000</td>
</tr>
<tr>
<td>Depreciation, RUB/cum. hours</td>
<td>896</td>
<td>325</td>
</tr>
<tr>
<td>Total cost of ownership (per 10,000 cum. hours), RUB</td>
<td>35 290 000</td>
<td>26 170 000</td>
</tr>
</tbody>
</table>

In order to substantiate the need for improvement, the developed nomenclature for estimating the cost of the LC [19] is of considerable interest, which is necessary for the consumer to plan and control the costs of acquisition, operation and disposal. Thus, among the costs of technical operation (TO) during the LC, the costs are presented, which in our opinion can be optimized by increasing the controllability and the introduction of modern diagnostic tools, information systems of technical condition (Table 4).
Table 4. The nomenclature of direct and indirect costs proposed for optimization with an increase in controllability and adaptability to diagnosis

<table>
<thead>
<tr>
<th>Name of costs</th>
<th>Cost determination</th>
<th>What costs can be optimized with increasing controllability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight</td>
<td>The costs of bringing the product into a state of readiness for its intended use and maintaining it in this state from the start of operation to its termination, including direct maintenance and repair costs</td>
<td>Part of the costs of maintenance and repair of the product, due to the payment of the personnel employed in the performance of labor</td>
</tr>
<tr>
<td></td>
<td>Part of the costs of maintenance and repair of the product, due to the payment of the personnel employed in the performance of labor</td>
<td>Part of the cost for the maintenance of product due to the repair of the components being restored</td>
</tr>
<tr>
<td></td>
<td>The costs associated with the transportation of the product during the work on the maintenance and repair of the product</td>
<td>The costs associated with the transportation of the product during the work on the maintenance and repair of the product</td>
</tr>
<tr>
<td>Indirect</td>
<td>Costs incurred at the operational stage, costs for management personnel, purchase and repair of equipment and tools, verification of measuring instruments, maintenance of infrastructure</td>
<td>Costs for the purchase of the maintenance and repair funds carried out before the start of operation of the product</td>
</tr>
<tr>
<td></td>
<td>Costs for the purchase of the maintenance and repair funds carried out before the start of operation of the product</td>
<td>Part of the indirect costs for technical exploitation related to the maintenance of infrastructure, repair of equipment and tools, verification of measuring instruments</td>
</tr>
</tbody>
</table>

In order to obtain the necessary information for assessing the technical condition of equipment online, it is necessary to implement at the manufacturing stage a predicative system for monitoring the technical condition of individual components and assemblies in real time (using already installed sensors) [20, 21]. And if the controlled parameters of the condition go beyond the established limits, maintenance is performed in order to minimize the consequences (group numbers) of failures, which significantly reduces the costs of their elimination and the time of events, optimizes the load of logistics and service services, and also encourages the consumer to comply with the rules of operation of the product.

Thus, in our opinion when determining the consumer properties of equipment, it is necessary to evaluate:
- variants of diagnostic fitness solutions (DF) [15];
- the presence of standard control elements (SCE) [22].

For example, the transition from DF solutions from 6 to 2...1 or from SCE 1 to SCE 6...11 will allow us to obtain diagnostic information, but eliminate the time to prepare for diagnosis by using a measuring system with software and computing devices, which in turn will increase consumer qualities due to:
- reducing the operational complexity of diagnosis;
- reduce diagnostic costs;
- it will increase the volume and reliability of information and reduce uncertainty in determining the need for maintenance.

In order to increase the level of suitability, it is necessary to make minor changes to the design of components and assemblies already at the design or modernization stage, which will slightly increase the cost of products, however, during the LC, the cost of assessing the technical condition will significantly decrease due to reducing the complexity of diagnostics (including resource) and reducing the cost of eliminating the consequences of failures. Installing built-in diagnostic tools that automatically continuously transmit technical condition data through a telemetry terminal and the complexity of diagnostics becomes minimal [23, 24].

The diagnostic system should ensure minimization of costs during operation associated with the use of individual systems and pieces of equipment, which is characterized by the coefficient of repair-in-place diagnosis (Cr.d.) [15].

At the same time, when determining consumer properties, the total number of controlled parameters (Pc) and the number of controlled parameters should be indicated, for the
measurement of which disassembly and installation work (Pi) is not required. The coefficient of repair-in-place diagnosis is determined by the formula:

\[ Cr.d. = \frac{Pc}{Pi}; \]

Accordingly as suggestions, the indicators of repair-in-place diagnosis can be as follows: Cr.d. = 0...0.5 is low; Cr.d. = 0.5 ... 0.8 is medium; Cr.d. = 0.8...1.0 is high.

The diagnostic suitability assessment system minimizes the continuous costs associated with the use of individual systems and pieces of equipment during operation, and reduces the level of costs going to eliminate the consequences of failures.

It is established that when assessing consumer properties under machine and tractor station conditions, structural and production failures are mainly evaluated, and under conditions of real long-term operation, with an increase in the operating time of equipment, operational failures begin to prevail. This is largely due to the lack of ability to monitor compliance with the rules of operation of equipment, as well as the recommendations of manufacturers of components and assemblies.

Since the resource of components and aggregates is greatly influenced by the particular values of the resources of individual components (bearings, friction discs, hydraulic drive units, etc.). Therefore, a diagnostic system is needed that allows us to determine the degree of resource consumption in work cycles, as well as monitor the conditions required for this work as the condition of filters and the temperature of the working fluid.

In practice, the implementation of the proposals is carried out using a system of counters-indicators developed in the Federal Scientific Agro-Engineering Center VIM transmitting data to a telemetry terminal [24, 25].

Processing of the received data is carried out using the developed software, which will allow evaluating not only diagnostic parameters, but also determining the quantitative characteristics of the loading of individual units during work, which will allow assessing the technical condition and timely preventing failures, managing reliability, as well as more accurately identifying consumer properties and cost of ownership of machines.

On the base of analysis of Standards and Technical Documentation [26-28] and the results of staged experiments, proposals have been developed for a system for monitoring compliance with operating rules, which according to our opinion allow us to determine the general technical condition and compliance with maintenance procedures during ordinary operation of equipment to reduce the likelihood of structural, production and operational failures (Table 5).

**Table 5. Proposals for a system for monitoring compliance with the rules of operation**

<table>
<thead>
<tr>
<th>No.</th>
<th>Purpose of control</th>
<th>Means of control</th>
<th>Justification of the event</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Careful attitude to technology (driving style)</td>
<td>Eco Driving system of the telemetry terminal</td>
<td>Reduction of the probability of failures of groups II, III of aggregates (gearbox, drive axles and carrier and brake system)</td>
<td>If the threshold values of accelerations, decelerations are exceeded, a point assessment is made</td>
</tr>
<tr>
<td></td>
<td>Compliance with the operating rules for the condition of the working fluids of the units during operation, control of the temperature ranges of the working fluid</td>
<td>Compliance with the operating rules for tire pressure during agricultural and transport work</td>
<td>Compliance with the rules of operation and monitoring the condition of filters</td>
<td>Compliance with the operating rules for the level of crankcase gas pressure</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>Counter-indicator and a set of sensors</td>
<td>Reducing the probability of failures of groups II, III of aggregates (internal combustion engines, gearbox, drive axles, turning and hitching hydraulic systems), providing recommendations from manufacturers of hydraulic drive units, increasing fuel efficiency</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, seasonal maintenance, a percentage assessment is made</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment is carried out</td>
</tr>
<tr>
<td>3</td>
<td>Counter-indicator and a set of sensors</td>
<td>Reducing the probability of failures of the I, II groups of the running system</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment is carried out</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment is carried out</td>
</tr>
<tr>
<td>4</td>
<td>Counter-indicator with a set of sensors</td>
<td>Reducing the probability of failures of groups II, III of the internal combustion engine, gearbox, hydraulic suspension drive</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment is carried out</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment is carried out</td>
</tr>
<tr>
<td>5</td>
<td>Counter-indicator with a set of sensors</td>
<td>Reducing the probability of failures of groups II, III of the internal combustion engine</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment is carried out</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment is carried out</td>
</tr>
<tr>
<td>6</td>
<td>Counter-indicator with a set of sensors</td>
<td>Reducing the probability of working in an uneconomical mode of operation of the internal combustion engine, helping the operator when choosing a transmission</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment is carried out</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment is carried out</td>
</tr>
<tr>
<td>7</td>
<td>Counter-indicator with a set of sensors</td>
<td>Reducing the probability of failures of groups II, III of the internal combustion engine, gearbox, hydraulic systems of rotation and suspension</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment of the level of the declared resource characteristics is carried out</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment of the level of the declared resource characteristics is carried out</td>
</tr>
<tr>
<td>8</td>
<td>Counter-indicator with a set of sensors</td>
<td>Reducing the probability of failures of groups I, II, III</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment is made</td>
<td>The level of compliance with the rules of operation, the quality of the daily maintenance, an expert assessment is made</td>
</tr>
</tbody>
</table>
We believe that in order to create conditions for effective management of consumer properties of agricultural machinery during life cycle, it is necessary to optimize the costs of both manufacturers and consumers on the basis of increasing controllability and adaptability to diagnostics, which ultimately will allow determining the level and managing the technical condition and reduce the cost of ownership of machines by reducing maintenance and repair costs [29, 30].

4 Conclusions

1. The carried out analysis of the Standards and Technical Documentation for the development of proposals for the preservation of consumer properties and efficiency of agricultural machinery showed that in order to improve the consumer qualities of machinery during the life cycle, it is necessary to increase the level of controllability and adaptability to the diagnosis of individual systems, pieces of equipment and aggregates to assess the technical condition with the determination of the degree of use of the guaranteed resource, compliance with the operating rules recommended by the manufacturer.

2. When assessing the consumer properties of equipment, they are not taken into account:
   - failures of the I group of complexity prohibiting the operation of equipment, parameters of technical and environmental safety of such failures, categories of severity of the consequences of failures;
   - availability in the operating instructions of the approved nomenclature of control and diagnostic and service equipment for evaluation the technical condition and carrying out maintenance work, resource diagnostics;
   - availability of built-in systems for detecting failures, determining their criticality and localization of malfunctions in the form of a coefficient of repair-in-place diagnosis (Cr.d.).

3. Proposals have been developed for a system for monitoring compliance with operating rules, which according to expert estimates allow monitoring the general technical condition and compliance with maintenance procedures during the ordinary operation of equipment, which can reduce excess costs of funds and time up to 3 times.

References


the technical condition of energy-saturated tractors under lease. Agroengineering. 2021. No. 6 (106). Pp. 4-10.


