Research and development of a probability mathematical wear model of automobile friction joints

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Abstract. The existing approaches related to the mathematical description of the wear process are analyzed. A new mathematical wear model for automobile friction joints, based on an infinite power series, has been substantiated. This model takes into account the random nature of the wear process and the nonlinearity of the wear accumulation during the breaking-in period and normal operation of the detail. It is convenient for engineering estimations and does not require complex calculations. The article is recommended for agricultural specialists, scientists, teachers, graduate students, undergraduates and students of agricultural universities for the program track "Agricultural Engineering".

1. Introduction

The wear process of automobile friction joints is very complex, since it depends on a large number of objective and subjective factors that combine in different ways in the specific conditions of using agricultural vehicles.

In order to identify the complete set of these factors, it is necessary to consider the mechanical system car-driver-road-operation mode-external inputs. In this case, a car is a mechanical system as a whole, a set of prefabricated units or joints and parts, depending on the goal of the research.

The wear phenomenon of automotive friction joints as a system can be represented as the following function:

\[ I = y(A, B, C, D), \] (1)

where \( I \) is the wear phenomenon of automobile friction joints as a system;

\( A, B, C, D \) are symbols that unite a group of factors (operational, structural, technological) determining the longevity of a car;

\( D \) – a symbol denoting the consideration of the influence of subjective driver characteristics.

Obtaining objective quantitative indicators characterizing the perception process of road conditions and the reliability of the driver is one of the main difficulties in solving the traffic safety problem.

2. Materials and methods

The fairly wide selection of research methods are at the disposal of researchers studying the process of perceiving information by the driver in real working conditions. The simplest of them is the subject's verbal report method, usually used at the first stage of studying some process. It allows obtaining the general ideas about the process and does not require special equipment [1,2].
The test driver can give answers to questions posed in advance in the course of fulfilling his usual production duties, or recalling his subjective feelings, state them in the answer form in special profiles. The accuracy of this method with a large number of tests is quite high, but the possibilities are limited: it can only be used to determine the driver’s subjective sensation of perceived stimuli and it is impossible to obtain objective data on the functional state of the driver at a particular point in time.

In addition, this method allows obtaining the information about the perception process discretely, rather than continuously. The method of studying the driver’s perception of road conditions through his decisions made under the influence of various combinations of the studied factors, mainly through changing the speed and trajectory of the car, is now widely used.

With its help, elements of roads are normalized and their combinations are selected, issues of ensuring traffic capacity of roads, organization and traffic safety are resolved.

There is no direct contact between the researcher and the driver when measuring the traffic flow. Therefore, studying the perception process is based on the blackbox principle. This is a disadvantage of this method. The driver’s process of perceiving road conditions can only be disclosed if it is possible to obtain objective data about him recorded from the driver himself. In this regard, research methods used in psychology, human physiology, and engineering psychology are of interest.

Of the large number of methods used in engineering psychology, those that satisfy at least two following requirements are of interest: they should give quantitative characteristics of the driver’s psychophysiological state and their use should not violate normal working conditions. Such assessment methods should provide not discrete, but continuous information on the functional state of the driver during movement. These include electrophysiological research methods: electroencephalogram (EEG), electrocardiogram (ECG), electromyogram (EMG), galvanic skin reaction (GSR), as well as oculography (OCG) and methods for assessing the functional state of the visual system. These are the critical flicker frequency (CFF), phosphene (the appearance of a sensation of flickering glow at the view field edges with direct irritation of the retina by alternating current).

The use of electrophysiological and psychological methods for studying the status of person’s central nervous system is based on theoretical principles that determine the measurement methodology. In road studies, ECG, GSR, OKG and partially EEG are commonly used as the main indicators reflecting the driver’s perception of road conditions. EMG, CFF, phosphene and driver tests are additional indicators. The effectiveness of using these indicators for a qualitative assessment of the driver’s sensory system has been proven in numerous studies.

### 3. Results and discussion

As a result of analyzing the wear phenomenon of automobile friction joints as a complex mechanical system, the following main factors determining their durability were identified: operational, structural, technological and subjective features of the driver (table 1).

**Table 1.** A brief description of the objective and subjective indicators determining the longevity of the car.

| Indicator type          | Brief description of the indicator                                                                                                                                                                                                 |
|-------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Operational             | The nature of the work performed; equipment operation modes; types and frequency of technical control actions; climatic conditions of the car operation; condition of lubricants and working fluids; condition of filtering and sealing elements |
| Constructional          | Friction type of working surfaces; loading condition; stress concentration; the presence of protective coatings; the presence of wear compensators; kinematics and dynamics of the car; balance of materials of joint members                                      |
| Technological           | The structure of the metal surface layer; surface treatment methods; the presence of residual stresses; joint build quality; the presence of technological contaminants (chips, scale, etc.) in the crankcases and tanks of the car, microgeometry indicators of friction surfaces |
| Subjective features of  | Level of professional training (qualification); anthropometric and psychophysical                                                                                                                                                    |
driver data (the efforts exerted on the control levers, the turn-on frequency of mechanisms; the reaction speed, driver lassitude, etc.)

As a result of the studies, it was also found that the most informative of the operational factors are the nature of the work performed and the operating modes of cars. The temperature, load, and speed operation modes of the joints, which determine the conditions of friction and wear of automobile members depend on these factors [3].

Control actions include adjusting, fixing and lubricating operations carried out during the car maintenance and repair. These factors can significantly reduce the negative impact of the external environment and internal processes that occur in structural elements and affect the longevity of the car.

Therefore, the wear rate of automobile friction joints largely depends on the content and frequency of maintenance. This is especially important for agricultural vehicles operating in difficult climatic conditions, such as increased humidity or dustiness of the environment, at low or high outdoor temperatures.

The friction and wear conditions of automobile friction joints are largely determined by the correspondence of lubricants and working fluids to the design of joints and to the operating conditions of agricultural vehicles. Therefore, it is necessary to strictly comply with the recommendations on the use of the main brands of lubricants and working fluids or their substitutes when carrying out maintenance and repair, as specified in the vehicle operating instructions [4, 5].

Equally important is the condition of fuels, lubricants and working fluids used in the corresponding systems of agricultural vehicles. When the vehicle condition indicators go beyond the set limits, it is necessary to replace the lubricant [6, 7].

The most important design factors determining the wear nature and wear intensity of automobile friction joints are the kinematics and dynamics of the agricultural vehicle. The friction type and the wear conditions of the friction joints depend on the relative displacement kinematics of the working surfaces of conjunction details [8, 9].

The dynamics of the agricultural vehicle determines the loading condition and the formation of internal stress fields in the materials of its details. The material balance of joint members has a decisive influence on their frictional interaction and, thus, on the durability of the car.

First of all, road conditions are considered as a factor determining the reliability of the driver.

The number of accidents in which driver errors are the main or concomitant cause remains quite high. These causes can be divided into two following groups: those related to the discipline of the driver and the features of the sensor system. The first reason is subjective and is a problem to be solved during the professional selection of drivers, as well as during the surveillance and traffic management by the police of the Ministry of Internal Affairs of the Republic of Kazakhstan. The second reason is objective, not depending on the will and desire of the driver. The accidents caused by the peculiarities of the driver’s sensory system can be eliminated, if the conditions under which the psychophysiological characteristics of the driver can cause untimely detection and decryption of the signal or can cause an error in the perception of the road conditions are excluded.

This is an engineering problem, but it is necessary to know the characteristics of the main indicators determining the personal qualities of the driver in order to solve it, as well as his perception of the road situation and the dynamics of their changes under the influence of working conditions.

Traffic safety is determined by the reliability of all elements of the car-driver-road complex. Reliability of traffic can be represented as the probability product of failure-free operation of all links in the car-driver-road system:

\[ R \times D \times C \times OE \times R, \]  \hspace{1cm} (2)

where R is the road;
D is the driver;
C is a car;
OE is the outdoor environment.
The failure-free operation probability of the car is also defined as the product of the $P_{A_i}$ failure-free operation probabilities of its individual conjunctions and assemblies:

$$P_A = P_{A_i}$$  \hspace{1cm} (3)  

where $P_A$ is a failure-free operation probability of a car;  
$P_{A_i}$ – failure-free operation probability of individual conjunctions and assemblies.

Road reliability is understood as its ability to provide safe calculated traffic at a speed close to optimal during a given service life. The probability of safe traffic at certain speeds for a given time is a quantitative assessment of road reliability. This probability depends on the probability of failure-free operation of all road elements, as well as on weather conditions that drastically change the transport and operational characteristics.

Reliability of the road itself as a part of the overall complex, as well as for the car, is expressed by formula (3) in general terms, and the $P_{A_i}$ multipliers mean the failure-free operation of individual road elements and the likelihood that its transport and operational qualities will not decrease to a hazardous value.

Calculating the reliability of the driver is much more difficult. The operator reliability is understood as the ability to perform specified functions in specified conditions. It is quantified by parameters (running hours, trouble-free life, total hours in service, etc.) and probabilistic characteristics (probability of failure-free operation, probability of failures, work intensity, etc.).

The ability to quickly and accurately make decisions in stressful situations, as well as the ability to quickly perceive and process information are the main indicators of operator reliability, which general and engineering psychologists suggest choosing depending on the type of operator activity.

A particular problem is the quantitative expression of operator reliability, which is defined by various researchers as the ratio of the numerical characteristics of any indicator at the moment to the average or optimal value. The operator’s productivity, his reaction time, and information processing speed are proposed as such indicators. According to numerous studies, operator reliability is quantified by the frequency of errors leading to failures, as well as by the duration or the accuracy of critical operations.

Knowing the exact quantification of driver’s reliability is not necessary for optimizing standards, road design methods and traffic management. For the practical use of this indicator, it is enough to know the qualitative indicators of the productivity dynamics of the driver and the correlation between the dynamics and road conditions.

The driver as the operator of the “driver-car-road-environment” (DCRE) system receives most of the information from the road, such as moving and stationary objects on the road, road signs, traffic lights, road surface conditions and traffic environment.

There is a continuous exchange of information in the DCRE system, an informative message is received by the driver from the car and the road, and a command message is received by the car from the driver. After performing control actions, the driver receives feedback on the results of these actions through feedback channels and performs the next necessary control actions in accordance with the changed situation. Thus, the DCRE system is a regulation system, in which the position of the car in relation to the road is a defining variable, the driver is a regulator, and the car is an adjustable object. All links of this system are interconnected, interdependent and determine the reliability of each other.

The reliability of the driver as a DCRE system operator depends on his ability to perceive and process the incoming information. Perceiving and transferring the information is carried out through the senses, such as vision, hearing, articular-muscular, vestibular and tactile senses, the olfaction, as well as the visceral analyzer, from which the cerebral cortex receives information from the internal organs. Each analyzer consists of peripheral, conductor and central departments. The peripheral part of the visual analyzer is the eyeball, for the auditory one it is the nerve endings of the inner ear, for the joint-muscular one it is the nerve endings (receptors) located in the muscles, tendons and articular surfaces. The peripheral divisions of analyzers perceive certain stimuli (light, sound, etc.) that are transmitted to the centers of the cerebral cortex, where mental processes arise, such as sensations of
light, sound, muscle tension, etc. The visual analyzer is of particular importance for the driver, up to 80...90% of all information is received through it. Joint-muscular, vestibular and tactile feelings are important. A smaller role is played by hearing and sense of smell.

Information transfer is determined by bandwidth, i.e. the maximum speed with which a communication channel can transmit information per unit time. The bandwidth of the visual channel is 20...70 bit/s, and is 0.6...0.8 bit/s for the auditory channel. The number of road signs installed on individual sections of the road should be no more than three.

In reliability theory, the main indicator of operational reliability is system failure. This term usually means the inability of the system to perform its functions when a signal is not received due to overload or failure of one of its blocks, as well as erroneous actions. According to the terms of the reliability theory, the driver’s failures are errors in perceiving and recognizing the objects of a road situation, making decisions, performing control actions that can create an emergency situation or cause an accident. The failures also are stopping work under the influence of stressful effects, violation of temporary operating modes.

The concepts of reliability and failure have a broader meaning regarding the driver, than mechanical or radio-relay systems. They include not only the actual failure due to overload, but also the change in the state of the driver’s body and his psychophysiological parameters under the influence of road conditions.

Most characteristics of operator reliability, which are psychophysiological functions, have only a qualitative assessment, but, despite this, they can be used as objective indicators of driver reliability, since the dynamics of their changes can be associated with the complexity of the road situation.

The influence of working conditions, personal qualities of the driver and his psychophysiological state on the reliability of work is presented in table 2.

Today's knowledge standard of the human psyche, the mechanisms of perceiving and processing the information still does not allow giving a quantitative unambiguous reliability evaluation of not only the driver, but also the operator in general.

| Table 2. Factors determining the reliability of the driver. |
|----------------------------------------------------------|
| **Operating conditions**                                  |
| Road                                                     |
| Location of the information medium in the driver’s field of vision |
| Road signs                                               |
| Optical orientation tools                                |
| Signalling                                               |
| **Driver’s personal quality**                            |
| Qualification                                            |
| Experience                                               |
| Professional knowledge                                   |
| **Psychophysiological state**                            |
| The status of the organs perceiving the information       |
| The dynamics of the functional states of the nervous system |
| Strength and stability of the nervous system              |
| Workability                                              |

Therefore, indirect indicators have to be resorted to when solving this problem. Such indicators are, for example, the speed of information processing and the time of simple and complex reactions.

Most studies about the traffic management field are aimed specifically at studying these indicators. The results of studies jointly conducted by engineers and psychologists are of significant interest to road workers. Moreover, it is already possible to eliminate dangerous places at the stage of road design and rule out situations that reduce driver’s performance by knowing the patterns of changes in individual indicators of driver reliability. The same data for the purposes of traffic management are the basis for the development of methods and means of transmitting information to the driver about road conditions and the recommended driving mode.
It is necessary to know the probabilistic change patterns of main characteristics of agricultural vehicles in time in order to analytically describe the random wearing of the friction joints. As applied to automotive friction units, these issues have so far been studied insufficiently [10].

The goal of the research was to increase the reliability and efficiency of using agricultural vehicles by researching and developing a probabilistic analytical wear model of automobile friction joints.

The research object was the technical operation process of agricultural vehicles in the auto fleet of the Krasnodar Territory.

The subjects of the study were methods to improve the reliability and efficiency of using agricultural Star 1142 vehicles at OAO “Dinskoe ATP” in the Krasnodar Territory by researching and developing a probabilistic analytical wear model for automotive friction joints.

The objectives of the study were as follows:
1) to analyze existing approaches related to the mathematical description of the wear process;
2) to substantiate a new analytical wear model for automotive friction joints based on an infinite power series.

In order to achieve the goal of the research, an analysis of scientific sources related to the analytical description of the wear process was carried out. Analyzing the published studies shows that significant progress in this direction has been achieved by scientists of the GNU “All-Russian Research Institute of Agricultural Mechanization” VIM, GNU “GOSNITI” and other research institutes and educational institutions.

Let us now consider the issue of substantiating a new analytical wear model.

A mathematical description of the wear process requires at least three equations. The first of them should satisfactorily express the mathematical expectation of the random wear accumulation process over time, i.e., the nonrandom component of the wear process. The second equation should satisfactorily express the upper confidence bound of the random process, i.e. a curve about which (with a given degree of risk) it can be said that no implementation of the wear process will go above it. The third one should express lower confidence boundary of the wear accumulation process. These equations together form a probabilistic analytical model of the wear process.

Studying the statistical wearing laws of the details of agricultural vehicles allows formulating the basic requirements for an analytical model. This model should take into account the random nature of the wear process and the nonlinearity of the wear accumulation during the running-in and normal operation of the detail.

It should be convenient for engineering calculations and not require complex calculations. The model should not contradict experience, which is important. The more accurately the analytical model corresponds to the objectively existing wearing of details under operating conditions, the better it is.

Most often in the scientific literature there are linear and non-linear models, in which the mathematical expectation of a random wear process is described either by a polynomial of the second and third degree, or by an exponential equation. For example, the following dependencies can be used most often:

\[ y = y_0 + bt; \]
\[ y = y_0 t^b; \]
\[ y = y_0 \left[ 1 - \exp\left( \frac{t}{b} \right) \right]; \]
\[ y = y_0 \exp(-bt) \]

In all these dependences, wearing is characterized by the parameters \( y_0 \) and \( b \). Linear dependence (2) is very convenient for practical use, as well as dependences that are easily transformed to a
linear form, such as (5) and (7).

However, the dependence of the average wear of the samples and real automobile details on the kilometrage indicates the nonlinear nature of wearing.

A separate limited section of the wear curve could be described by a linear equation. However, an overly optimistic forecast is obtained when extrapolating the linear equation outside the area it was built for. Such forecast does not exclude the possibility of prematurely reaching the wear limit.

It can be assumed that while operating the joints of agricultural vehicles, their wear rate $\bar{V}$ is a function of the accumulated wear $\delta$:

$$\bar{V} = \frac{d\delta}{dt} = f(\delta),$$

(8)

where $\bar{V}$ is the wear rate of the automobile friction joint; $t$ is the operation time of the joint.

Equation (6) can be represented as an infinite power series:

$$\frac{d\delta}{dt} = c + k\delta + k_2\delta^2 + \ldots + k_{n-1}\delta^{n-1}.$$  

(9)

Only the first member of this series is used in the linear model, assuming that the wear rate remains constant throughout the entire period of normal operation.

A strong linear correlation between the wear rate of automobile details and accumulated wear allows managing with only the first two members of series (9) and neglecting the rest. After transforming equation (6) and integrating its left and right parts with respect to time and wear, and assuming that the average wear value is $h_1$ at operating time $t_1$, the following can be obtained:

$$t - t_1 = \frac{1}{k} \ln \frac{c + k\bar{\delta}}{c + k\bar{\delta}_1}.$$  

(10)

We now proceed to the decimal logarithms:

$$t - t_1 = \frac{1}{k \lg e} \ln \frac{c + \bar{\delta}}{\frac{c}{k} + \bar{\delta}}.$$  

(11)

Let us set $\frac{1}{k \lg e} = A$; $\frac{c}{k} = h$. By substituting these values in equation (10) and solving it with respect to average wear $\bar{\delta}$, the exponential equation expressing the mathematical expectation of the wear process is obtained:

$$\bar{\delta} = (\bar{\delta}_1 + h)10^{\frac{t - t_1}{A}} - h.$$  

(12)

Coefficient $A$, which is measured in kilometrage units (km), determines the shape of the wear curve. It is called the longevity coefficient. The $h$ coefficient is measured in units of wear. It determines the position of the curve relative to the origin and is called the displacement coefficient. Its value is equal to the distance from the origin to the asymptote of this curve, taken with the opposite sign.

The following wear rate equation is obtained after differentiating equation (12):

$$v = \frac{d\delta}{dt} = \frac{\bar{\delta}_1 + h}{A \lg c}10^{\frac{t - t_1}{A}}.$$  

(13)
Exponential equation (9) assumes a normal distribution of wear for any moment in time. In this case, the upper confidence limit of the wear process can be described by the same exponential equation, by substituting the upper confidence limit of this random variable instead of the mathematical expectation of the initial wear $\delta_1 = \bar{x} + t_0 \sigma_1$:

$$\delta' = (\bar{x} + t_0 \sigma_1 + h)10^{\frac{t}{T}} - h,$$

(14)

Where $\delta'$ is the current upper confidence limit of wear;

$\sigma_1$ is the standard deviation of wear during the work duration $t_1$;

$t_0$ is a tabular coefficient depending on the accepted confidence coefficient $\beta$.

The lower confidence limit of the wear process is obtained by substituting the lower confidence limit of the initial wear into equation (8):

$$\delta^* = (\bar{x} - t_0 \sigma_1 + h)10^{\frac{t}{T}} - h,$$

(15)

where $\delta^*$ is the current lower confidence limit for wear.

Equations (14) and (15) should limit the field, within which not less than $\beta$ of 100% of all possible wear cases for the investigated details are enclosed. By substituting the values of the upper and lower confidence limits at time $t_2$ in the equations (14) and (15) instead of $\delta'$ and $\delta^*$, and solving them together, the expressions for the constants $A$ and $h$ should be obtained:

$$A = \frac{t_2 - t_1}{\lg \frac{\sigma_2}{\sigma_1}};$$

$$h = \frac{\bar{x}_2 - \bar{x}_1 \cdot \frac{\sigma_2}{\sigma_1}}{\frac{\sigma_2}{\sigma_1} - 1},$$

(16)

(17)

where $\bar{x}_2$ and $\sigma_2$ are the average wear and its standard deviation at time $t_2$, respectively.

Equations (12) - (17) allow determining the equation of expectation and the equation of wearing confidence limits for the node in random real-life operating conditions. It is achieved by means of a statistical study of the wear of details that were in operation for two operating time values $t_1$ and $t_2$, which are quite different from each other.

The results of measuring the wear of cylinder liners of a 359 M engine are presented in Figure 1. The wear accumulated during a long operation period of agricultural Star 1142 vehicles at OAO “Dinskoe ATP” in the Krasnodar Territory.

5 engines (30 cylinder liners) were studied since they were manufactured till the vehicle reached mileage of 250 thousand km.

Moreover, wear measurements of cylinder liners were carried out every 50 thousand km.

The figure shows a good agreement between the theoretical and actual values of the average wear (solid line) of the cylinder liners at all studied mileage intervals. Almost all experimental points lie below the upper confidence limit (dashed line), while the extreme points copy its shape.

The results of physical modeling of the wear process of articulated and splined joints were performed during testing on laboratory stands for experimental verification of the mathematical model considered above. The results of statistical studies of the wear of various details in agricultural vehicles in real operating conditions were also used.
Studies have also proven that the driver’s productivity is influenced by his individual characteristics, working conditions and features of the information flow.

Individual features include psychophysiological and personal qualities, the level of driver’s professional training, physical data and state of health.

The working conditions include features of the workplace (location of controls, instruments, seats), visibility, serviceability of equipment, microclimate in the cabin (humidity, air temperature and air flow velocity), road condition, traffic intensity and speed, level of traffic organization and other.

Features of the information flow are characterized by the following:
- spatial arrangement of information sources;
- information flow rate;
- ease of perceiving the information, which is determined by the size, contrast, relative position and illumination of numbers, words, signs, etc.

Upon receipt, processing of information and its implementation by the driver, there are five main stages.

The first stage is the reception of information. At this stage, the active detection, isolation and perception of the necessary signals from the environment takes place.

The second stage is information processing. An important factor in the information processing is forecasting, i.e. predicting the changes in traffic conditions and the implementing the actions that anticipate the possibility of an emergency.

The third stage is decision making. If after assessing the situation it follows that the solution is unambiguous, then the selection of solution does not occur.

The fourth stage is the implementation of decisions. This can be expressed in actions by the controls in accordance with the decisions taken, in the termination of the performed action, change in its amplitude or direction, maintaining movement in the previous mode.

The fifth stage is control over the performed action. It is carried out using feedback, which is informative information about the results of the driver's control actions.

![Figure 1](image_url) Wear accumulation curves of cylinder liners in the engine of 359 M Star 1142 agricultural vehicles.

4. Conclusions
To sum up, the considered exponential probabilistic model quite satisfactorily describes the wear process of automobile friction joints and can be used to predict their wear and durability.
The analysis of existing approaches related to the mathematical description of the wear process was carried out, a new analytical wear model of automobile friction joints based on an infinite power series was substantiated. The analysis of scientific and literary sources related to the mathematical description of the wear process was carried out.

Studies have also proven that the driver’s productivity is influenced by his individual characteristics, working conditions and features of the information flow.

There are five main stages upon receiving, processing and implementing the information by the driver.

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