Theoretical aspects of diagnostics of car as mechatronic system

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Abstract. The article describes transformation of mechanical systems of automobiles into mechatronic ones due to application of electronic control systems. To assess the relationship of mechanical and electronic components of the mechatronic systems with regard to their technical states, the method of equivalent elements was employed. A mathematical model of changes in the technical state of equivalent elements was developed. It allowed us to present changes in operation capacity in a graphic form. The analytical model is used to ensure operating capacity potential stability for the mechatronic system. For this purpose, new resources were identified with regard to the information ‘field’. Therefore, a new approach to the systematization of knowledge about mechatronic transport systems (D-C-R-E system) is required. The D-C-R-E system is examined as a separate unit. The article describes Information unit formation based on the physical component of the D-C-R-E system and external information which is collected and processed in the Information Diagnostic Center (IDC). Using probability theory and Boolean algebra methods, the authors obtained a logistic model describing information relations between elements of the upgraded D-C-R-E system and contribution of each component to the road safety protection. The logistic model helped formulate main IDC tasks. Implementation of those tasks was transformed into the logical sequence of data collection and analysis in the IDC. That approach predetermined development of the multi-level diagnosing system which made it possible to put in order existing and improved image identification methods and algorithms and to create a diagnosing method for mechatronic systems of cars which reduces labor content and increases accuracy. That approach can help assess the technical state of vehicles with characteristics of mechatronic systems and their transport and environmental safety.

1. Introduction
At present, issues of road safety and environmental protection are typical for transport systems and connected with the technical state of vehicles /1,2,3/. Diagnostics issues for mechanical systems have been already studied by many researchers. However, mechanical systems of cars were transformed into mechatronic ones as a result of the technological evolution /4,5,6/. Due to that transformation, the
system took on new properties: wear ($K_W$) of the mechanical part (MP) is offset by the electronic control system of the mechanical part (ECSMP) which depends on the technical state.

2. Methods and materials.

Technical states of these systems cannot be compared directly, so the method of equivalent elements can be used instead. An element of the same size – an area of the equivalent figure – can be used as an equivalent. It can be illustrated with two figures of arbitrary shapes (Fig. 1) which initially had areas $S_1$ and $S_2$ characterizing the initial states of the systems. Depending on the properties of these systems, their areas increase (ECSMP self-learning and correcting) and decrease (MP wear simulation). The area of the rectangular shape was taken as an example.

![Figure 1. Relationship of changes in the ECSMP and MP areas.](image)

Changes in the MP area and technical state can be presented as an integral with the initial value at point 0 and final value $K_W$. The ESCMP area presents the working MP control area, and its changes are wear compensation. It is presented as an integral with the initial value at point 0 and final value $K_A$. Integral components maintain the total area constant which can be presented as:

$$S_\Sigma = S_1 + \int_0^{K_A} S_1 \Delta t + S_2 - \int_0^{K_W} S_2 \Delta t$$

where $S_1$ – initial state of the ECSMP;

$\int_0^{K_A} S_1 \Delta t$ – ESCMP self-learning and correcting.

$S_2$ – initial state of the MP;

$\int_0^{K_W} S_2 \Delta t$ - wear of the MP.

The total area of the figures is an equivalent of the technical state of the system. It presents the operating capacity potential of each element and the entire system. Therefore, one can turn from the equivalent model of the area of the figures presenting changes in the technical states to the operating capacity potential of the system.

The graphical model for maintaining operating capacity potential (OCP) of mechatronic systems is based on the assumption that the compensation of the ECSMP has limited value $K_A^{max}$. After achieving that value, the system behaves like a conventional mechanism rather than an adaptive one. Early transition to the limited compensation can result from the non-coincidence of initial characteristics of the components of mechatronic systems expressed in $\Delta$ (Fig. 2). $\Delta$ can be compensated by changing the caliber values of the ECSMP during running-in period. While in operation, $K_H^{max}$ can be also changed by reprogramming ($K_{R}$) of the ECSMP during scheduled maintenance (S). Thus, the graphical model is used to assess decrease of the rate change for $K_W$ and operating capacity potential stability for the mechatronic system until major repairs (MR).
Figure 2. Maintaining operating capacity potential of mechanical and mechatronic systems.

$K_A^{\text{Ul}}$ – changeable limited value of the correcting coefficient;
$K_R$ – coefficient of the ECSMP changed during scheduled maintenance $S$;
$K_W$ – MP wear rate change coefficient;
$\Delta$ – non-coincidence of the initial characteristics of the components of mechatronic systems;
$OCP(t)_{\text{sist}}$ – operating capacity potential of the mechatronic system;
$OCP(t)_{\text{stn sist}}$ – operating capacity potential of the conventional system.

$T_R$ – system’s operating time during running-in;
$T_{\text{Exp}}$ – system’s operating time during main operation period.

Transition to the analytical model of maintaining operation capacity of the mechatronic system can be presented as:

$$OCP (t) = (K_R \cdot K_A^{\text{Ul}} + K_A + \Delta) \cdot OCP_{\text{ECSMP}}(t) + K_W \cdot OCP_{\text{MP}}(t) \quad (2)$$

At the suggested level of maintaining operating capacity potential of the mechatronic system, the graphical model shows that the operating capacity potential is a constant value $\Pi(t) = \text{const}$ providing that the ECSMP and MP are in good working order.

$$OCP (t) = \text{const, if } D_1 = D_1 \quad (3)$$
or

$$OCP (t) \neq \text{const, if } D_1 = D_2 \quad (4)$$

Thus, to maintain the operating capacity potential of the mechatronic systems, early fault recognition is required. Technical diagnosis and prediction with minimum resolution of impacts on the system are used. Let us consider the mechanism for receiving diagnostics information in the Driver – Car – Road – Environment (D-C-R-E) system /7,8/.

Mechatronic systems combine mechanical and electronic units creating new relations inside and around the information field which allowed going to a new development level. It required a new approach to the systematization of knowledge about mechatronic transport systems with regard to the D-C-R-E system, as new knowledge causes contradictions in the system. To study the contradictions in the D-C-R-E system, let us analyze the structure of each unit.
ENVIRONMENT includes natural climatic conditions (ambient temperature, humidity, atmosphere pressure, etc.) and external data influencing the D-C-R system. External information environment develops outside the system and can influence it. For example, GPS, radio station or traffic jam data are external information sources.

ROAD includes road conditions (road quality, road defects, number of road lines, etc.) and road information (traffic management and technical traffic management means) which influence the D-C system.

DRIVER includes psychophysiological health of the driver and information s/he receives from the C-R-E system. Psychophysiological state of the driver refers to her/his health at a given instant. Information s/he receives influences decision making processes when driving.

AUTOMOBILE includes design solutions (output design and production parameters) and technical state data transferred to the dashboard or absorbed through senses.

Therefore, each unit has a physical component presenting its technical aspects and information component presenting its ‘information field’. Taking the above-mentioned information into consideration, the existing system can be upgraded as follows (Fig. 3).

INFORMATION can be treated as a separate unit in the upgraded D-C-R-E system shown in Fig. 3. It can be formed from the physical component of the D-C-R-E system and external information collected and analyzed in the IDC (Fig. 4).
The functional role of INFORMATION: data collection from the D-C-R-E system, data transfer to the IDC where data are processed, data communication to the driver for decision making.

Hardware tools for data processing and transferring are a physical basis for that unit. System upgrade increases its no-failure operation probability \( P /9, 10/ \). Disjunction of all system elements determines \( P \) and can be presented as:

\[
P = (P(D) \lor P(C) \lor P(R)) \land P(E) \land (P(I) \lor P(IDC)) \tag{5}\]

where
- \( P(D) \) – driver’s psychophysiological state dependent probability of no-failure operation;
- \( P(C) \) – car’s health dependent probability of no-failure operation;
- \( P(R) \) – road dependent probability of no-failure operation;
- \( P(E) \) – environment dependent probability of no-failure operation;
- \( P(I) \) – data transfer hardware dependent probability of no-failure operation;
- \( P(IDC) \) – IDC dependent probability of no-failure operation.

The expression shows the contribution of each parameter to the total road security (RS) level and operating capacity potential maintenance with regard to the individual probability of no-failure operation of system elements.

It can be presented as:

\[
P(RS) = E \land (D \lor C \land R) \tag{6}\]

The model can be transformed in the following way:

\[
P(RS) = E \cdot (D + C + R) \]

\[
P(RS) = E \cdot I_E \cdot (D + C \cdot I_C + R \cdot I_R)
\]

\[
P(RS) = E \cdot I_E \cdot D + E \cdot I_E \cdot C + E \cdot I_E \cdot R \cdot I_R
\]

or

\[
P(RS) = D \leftarrow I_E \left\{ \frac{e^{-I_E \cdot I_C}}{e^{I_E - I_R}} \right\}
\]

The model describes information relations between the elements of the upgraded D-C-R-E system and contribution of each element to the road safety protection. Individual technical state of the car is most significant for that parameter providing that a certain number of cars are on the same road section. The logistic model shows that car health information is transferred to the information field and then communicated to the driver for optimal decision making.

Data processing in the IDC determines the extent of information. Based on the logistic model, the main IDC tasks are as follows:
1. Communication of all data to the driver;
2. Communication of individual data to the driver;
3. Communication of minimum data to the driver.

To perform the first IDC task, data collection, decoding and communication software and hardware tools are required. Task performance will depend on professional skills of the driver or engineering team.

To perform the second and third tasks, a multilevel approach to data processing which would divide individual and minimum information communication in space is required.

Need for individual information is due to the lack of maintenance departments at small transport enterprises.

Development of the minimum extent of information aims at assessing individual technical conditions of private cars. Therefore, information should be communicated to the driver on a regular basis in case of faults or changes in diagnostic parameters according to the following pattern:
- diagnosing (faults);
- type and volume of repair works;
- the nearest maintenance station.

Diagnosing is the most responsible and demanding process. To develop a logical sequence of diagnosing, one can use a mathematical model of statistical distribution of faults in time. That distribution does not take into account individual characteristics of car operation which causes sudden faults.
where \( P(A_i) \) – no-failure operation probability for the i-th system forming a part of the vehicle; 
n – number of mechatronic systems forming a part of the vehicle.

Constant or regular IDC-based control of the complex diagnostic system parameter can eliminate sudden faults of the i-th system. That parameter specifies the state of the object given its limited value.

With regard to sudden faults of the i-th system, equation 8 can be written in the form:

\[
P(A_i) = P(t)_i \cdot (1 - \frac{d_i}{d_{np}})
\]

where \( d_i \) – complex diagnostic parameter characterizing the state of the i-th system; 
\( d_{np} \) – limited value of the complex diagnostic parameter.

Diagnostic parameters \( d_i \) determine the coefficients of complex object image recognition parameters \( K_{ki} \). The amount of those coefficients is determined for each mechatronic system on an individual basis. The coefficients of complex object image recognition parameters are calculated by formula:

\[
K_{ki} = \frac{d_{np} - d_i}{d_{np}} \cdot 100\%
\]

where \( d_i \) – complex diagnostic parameter characterizing the state of the i-th system; 
\( d_{np} \) – limited value of the complex diagnostic parameter.

These coefficients can divide the space into failure and no-failure areas. If the object is in \( D_2 \) of the failure area, the driver has to be questioned in order to identify current or former characteristics \( (Sn) \) of the object. Based on the information about the object for the long operation period, one can determine the probability of each feature identified by the driver in order to identify the failure sub-system \( (Q_i) \). Thus, one has a preliminary diagnosis of the failure sub-system of the object. Then the object is forwarded to the maintenance station with preliminary diagnosis \( Q_i \) where the diagnostician performs element-based diagnosing by calculating image recognition coefficients for elements \( K_{ei} \).

The image recognition coefficient for \( K_{ei} \) is calculated by formula:

\[
K_{ei} = \frac{d_i}{d_{np}}
\]

where \( d_i \) – complex diagnostic parameter characterizing the state of the i-th element; 
\( d_{np} \) – limited value of the complex diagnostic parameter of the element.

Having determined \( D_i \), one finds out if the failure element is a part of the failure subsystem area with preliminary result \( Q_i \). If this is the case, correcting learning of the preliminary stage does not occur. If this is not the case, correcting learning of the preliminary stage occurs.

From the viewpoint of information theory, uncertainty created by the finite scheme of the logical sequence is written in the form:

\[
H = \log_2 n
\]

where \( n \) – number of logical units.

The sequence of diagnostic data collection and processing is presented in Fig. 5.

From the viewpoint of information theory, uncertainty created by the finite scheme of the logical sequence is written in the form:

\[
I(r) = H - H(r) = I_{max}
\]

where \( H(r) \) – mean conditional entropy of the scheme state providing that check \( r \) is selected.

As far as in case of check \( r \) only two results \( r=1 \) and \( r=0 \) are possible, then:

\[
H(r) = p(r)H(r) + p(\overline{r})H(\overline{r})
\]

Check t follows check \( r \). It gives the largest volume of conditional information \( I(t/r) \) about the relative state characterized by \( H(t) \):

\[
I(t/r) = H(r) - H(t/r)
\]
\[ H(t/r) = p(t/r)H(t/r) + p(\tilde{t}/r)H(\tilde{t}/r) + p(\tilde{t}/\tilde{r})H(t/\tilde{r}) + p(t/\tilde{r})H(\tilde{t}/\tilde{r}) \quad (16) \]

Check selection lasts until the entropy becomes zero. Testing ends at stage \( K \) whose numerical value is calculated as:

\[ H = 0 \text{ or } \log_2 n - K = 0, \quad (17) \]

Then

\[ K = \log_2 n. \quad (18) \]

When \( n \neq 2^k \), then

\[ \log_2 n < K < \log_2 n + 1. \quad (19) \]

**Figure 5.** Logical sequence of diagnostic data collection and processing in the IDC.

Control points in mechatronic systems are distributed when dividing checks into logical units: monitoring, mechanical subsystems, electronic subsystems with electronic units and coupling chains, an element base with sensors and operating mechanisms. Depending on the nature of distribution of the branch of the formal search pattern, the authors have eight logical units. Based on (18), one can calculate the number of levels of the diagnosing system:

\[ K = \log_2 n \Rightarrow K = \log_2 8 \Rightarrow K = 3 \quad (20) \]

The method is used to create and develop a multi-level diagnosing system. System monitoring by complex output parameters is carried out at the upper hierarchical level of the system. In case of deviation of the specified values of these parameters from the regulatory ones, transition to the lower diagnosing system level occurs in order to identify a failure subsystem. At the next lower level, the technical state of the subsystem element is assessed and faults and their causes are identified /11/.

Diagnostics of mechatronic systems of cars is shown in Fig. 6.

Multi-level diagnosing system regulates employment of existing and improved diagnosing methods and algorithms /12,13,14/.

The multi-level diagnosing system reduces the time of technological processes for mechatronic systems whose technical state does not belong to the tolerance range of complex diagnostic parameters. Complex diagnostic parameters help distinguish between mechanical and electronic faults.
Figure 6. Multi-level diagnostics system for mechatronic systems.

Optimal procedure of fault identification, ensuring that the technical economic coefficient does not increase, is typical for the multi-level system. That coefficient can be written in the form:

$$K_{m→} = \frac{t_i}{c_i} \quad (21)$$

where $c_i$ – costs for diagnostic level $i$.

Costs should ensure system reliability and do not exceed costs for scheduled maintenance without diagnosing while ensuring the same reliability level. That condition can be written in the form:

$$C_i = C_d + C_r \leq C_{p-p} \quad (22)$$

where $C_d$ – unit costs at the $i$-th diagnostic level;
$c_r$ – unit costs for preventive maintenance;
$c_{p-p}$ – unit costs for scheduled and preventive maintenance.

3. Conclusion

The multi-level diagnosing system allows developing a diagnosing method for mechatronic systems which can reduce labor content and increase diagnosing accuracy and reliability.

That method takes into consideration the technical state of the vehicle with characteristics of the mechatronic systems and its transport and environmental safety.

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