Development of a model for improving operating performance of vehicles

Andrey Glushchenko¹, Alexey Khokhlov¹, Denis Molochnikov¹, Ilmas Salakhutdinov¹, Evgeny Proshkin¹, and Ilnar Gayaziev²

¹Ulyanovsk State Agrarian University named after P.A. Stolypin, 432017, Ulyanovsk, boulevard Novy Venets, 1, Russia
²Kazan State Agrarian University, 420015, Republic of Tatarstan, Kazan, ul. Karla Markska 65

E-mail: denmol@yandex.ru

Abstract. The article describes the process of developing a model for improving the operational performance of vehicles. The development of the model is based on the interconnection and mutual influence of the basic elements of the vehicle. Since the internal combustion engine is the source of energy and the driving force, its performance directly affects the operation properties of the vehicle. In turn, they mainly depend on the nature of the working process and engine parameters. Therefore, a change in the technical and operational indicators of the engine will entail a change in the operational indicators of the vehicle on which it is installed. An information model of the influence of engine parameters on vehicle operational indicators allows establishing that, for a certain time of operation and fixed values of operating modes, improvement of vehicle performance is possible by changing the technical and operational parameters of the engine. At the same time, considering the functioning model of the internal combustion engine as a certain multidimensional and multilevel system, it was found that the working process taking place in the engine and the design parameters of its mechanisms have the greatest impact on changing engine parameters. The main working process takes place in the engine cylinder. Therefore, the details of the cylinder-piston group will have the greatest impact on the change in the engine output parameters. The use of mathematical modeling in solving this problem allows developing a concept for improving the performance of a vehicle, and optimizing the process of choosing ways to upgrade a vehicle and engine.

1. Introduction

In recent years, in the Russian Federation, vehicle design has achieved great success both in terms of a quantitative increase in the production of vehicles and in terms of improving their design. The type of manufactured structures has expanded significantly, new, more advanced types of systems and assemblies for various purposes have been created and mastered in production, which are not inferior in terms of performance and, in some cases, superior to foreign manufacturers.

However, despite the achieved results, modern vehicles are far from perfect, and first of all, in terms of their operational indicators. Therefore, designers and manufacturers are faced with the task of improving operational performance. To solve these problems, it is necessary to have a complete understanding of the interconnection between the output operational indicators of vehicles with the processes and properties of the materials of the mechanisms of the machines’ basic elements.
2. Materials and methods of the research

The scientific substantiation for improving the operational performance of vehicles should be based on the interconnectedness and mutual influence of its main elements. The source of energy and the driving force is the internal combustion engine. The engines of vehicles operate at various (steady and unsteady) speed and load conditions, which significantly predetermine their operation performance. Engine performance has a direct impact on the performance of the vehicle. In turn, they mainly depend on the nature of the working process and engine performance. So, the thrust and speed properties of the vehicle are affected by engine power and torque, and the fuel and economic properties are affected by the effective engine efficiency coefficient. Therefore, a change in the technical and operational indicators of the engine will entail a change in the operational indicators of the vehicle on which it is installed (Figure 1) [1, 2].

In the model under consideration, the input (disturbing) parameters \( X \) characterize the set of technical and operational indicators of the engine (power, torque, fuel consumption) and are determined by the vector function

\[
X = \{x_1, x_2, x_3, x_4\}. \tag{1}
\]

The output parameters will characterize the performance of the vehicle \( Y \) and is determined by the vector function

\[
Y = \{y_1, y_2, y_3, y_4\}. \tag{2}
\]

Since the vehicle is operated in various climatic and road conditions (disturbing parameters \( e_i \)) and under various modes (disturbing parameters \( z_i \)), the resulting value of the parameters \( Y \) will be determined by the function

\[
Y = f(X, E, Z). \tag{3}
\]

Then the corrective effect on the controlled flows of \( Y \) can be represented by a system of equations:

\[
\begin{align*}
y(y_1, y_2, y_3, y_4) &= X(x_1, x_2, x_3, x_4) \pm E(e_i), \\
y(y_1, y_2, y_3, y_4) &= X(x_1, x_2, x_3, x_4) \pm Z(z_i). \tag{4}
\end{align*}
\]

Figure 1. Information model of the influence of engine parameters on the performance of the vehicle: \( X \) - technical and operational performance of the engine; \( x_1 \) - effective power, kW; \( x_2 \) - indicator power, kW; \( x_3 \) - torque, N \cdot m; \( x_4 \) - specific effective fuel consumption, g / kW \cdot h; \( Y \) - operational performance of the vehicle; \( y_1 \) - travel fuel consumption, l / 100 km; \( y_2 \) - vehicle acceleration, m / s; \( y_3 \) - dynamic factor; \( y_4 \) - environmental indicators (content of CO, CH); \( E \) - climatic and road operating conditions; \( Z \) - modes of operation of the vehicle.

In this case, the value of the resulting output stream (of operational performance of the vehicle), taking into account the impact of climatic, traveling and operational modes of operation, can be shown as

\[
Y = \psi(y_i) \cdot E(e_i) \cdot Z(z_i). \tag{5}
\]

where \( \psi(y_i) = \sum((x_i \cdot e_i) + (x_i \cdot z_i)) \) at \( i = 1, 2, \ldots, n(6) \).

And making the assumption that \( e_i = \text{const} \) and \( z_i = \text{const} \), i.e. that the operating conditions have a certain fixed value for a certain operating time of vehicles.

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As can be seen, to improve the operational performance of the vehicle, it is necessary to change the technical and operational performance of the engine.
In order to identify the most significant engine indicators that have the greatest impact on the performance of the vehicle, we consider the engine as a controlled parametric system [2-5].

The vehicle engine is a multidimensional object of control, since the number of input parameters it has is more than one, and each input parameter affects two or more output parameters. Therefore, the improvement of engine operating conditions can be carried out by improving the process parameters or the operating conditions of its mechanisms and systems. Both that and another will lead to increase of its indicators, and, accordingly, to improvement of operational performance of the vehicle on which it is installed.

Development of a functioning model of ICE.

The ICE functioning model can be represented as a certain multidimensional and multilevel system. Such a system will be formed taking into account the input and output processes. Moreover, part of the input processes is control and is determined by the n-dimensional vector \( A(a_1, a_2, \ldots, a_n) \), determining the parameters of the engine workflow (indicator pressure, amount of charge, etc.), and by the m-dimensional vector \( B(b_1, b_2, \ldots, b_m) \), determining parameters and design features of its mechanisms (materials and parameters of CPG, crank gear, gas distribution mechanism, etc.). The input impact stream represented by the k-dimensional vector \( E(e_1, e_2, \ldots, e_k) \) is uncontrollable and characterizes the climatic and road conditions in which the engine is operated (Figure 2) [6-8].

The output characteristics of the system are determined by the i-dimensional vector \( A'/c_1', c_2', \ldots, c'_i \) and \( B/(c'_{i1}, c'_{i2}, \ldots, c'_{ij}) \), representing, respectively, technical and operational and fuel and economic indicators of the vehicle on which the engine is installed.

The output p-dimensional vector \( K_{TOI} (P_1, P_2, \ldots, P_r) \) contains the criteria for a comprehensive assessment of the technical and operational indicators of the system under consideration. The scalar output characteristics of the \( K_{TOI} \) vector, which form the engine assessment, will depend on the scalar vector values of the input flows, which have probably statistical parameters and form boundary values, within which the \( K_{TOI} \) functional will undergo a change.

Such a system reflects not only the known flows \( A(a_1, a_2, \ldots, a_n) \) and \( B(b_1, b_2, \ldots, b_m) \), but also allows you to take into account the influence of the output flows \( A'(c'_{i1}, c'_{i2}, \ldots, c'_i) \) and \( B/(c'_{i1}, c'_{i2}, \ldots, c'_{ij}) \), a causal relationship of their formation and influence on the output flow of the thermoelectric generator.

![Figure 2. Multiparameter model for the formation of technical and operational indicators of internal combustion engines.](image-url)
In the proposed model, the output flows $A(c', c_2', ..., c_i')$ and $B(c'^i, c'^2i, ..., c'^ji)$ will be controlled parameters, and their scalar vector values can be considered as boundary conditions in which the control flows $A$, $B$ and $K_{TOI}$ can be most effectively changed.

The proposed model allows us to take into consideration the influence of the output parameters $A(c', c_2', ..., c_i')$, and $B(c'^i, c'^2i, ..., c'^ji)$ to and determine their influence on the output factorial of $K_{TOI}$ and controlled flows $A$ and $B$. Moreover, scalar-vector values of controlled flows $A (a_1, a_2, ..., a_n)$ and $B (b_1, b_2, ..., b_m)$ will form the limits intervals of output streams $A (c', c_2', ..., c_i')$ and $B (c'^i, c'^2i, ..., c'^ji)$.

\[
K_{oc} = f(A, B, Y, A', B').
\]  

(7)

The output streams $A'$ and $B'$ form a feedback system expressed by the streams $X$ and $Y$, taking into account the restrictions established by $K_{TOI}$ at $0 < p \leq 1$:

\[
\begin{align*}
\exists(x_i) &= A'(c_1', c_2', ..., c'_i) \cdot K_{TOI}(P_1, P_2, ..., P_p) \\
Y(Y) &= B'(c'^i_1, c'^i_2, ..., c'^i_j) \cdot K_{TOI}(P_1, P_2, ..., P_p).
\end{align*}
\]  

(8)

Then the corrective effect on controlled flows $A$ and $B$ can be represented by a system of equations:

\[
\begin{align*}
A_X(a_1, a_2, ..., a_n) &= A(a_1, a_2, ..., a_n) \pm \exists(x_i), \\
B_Y(b_1, b_2, ..., b_m) &= B(b_1, b_2, ..., b_m) \pm Y(Y), \\
A_Y(a_1, a_2, ..., a_n) &= A(a_1, a_2, ..., a_n) \pm Y(Y), \\
B_X(b_1, b_2, ..., b_m) &= B(b_1, b_2, ..., b_m) \pm \exists(x_i).
\end{align*}
\]  

(9)

In this case, the value of the resulting functional can be shown as

\[
K_{TOI} = (P_1, P_2, ..., P_p) = \psi(c) \cdot \exists(x_i) \cdot Y(Y).
\]  

(10)

where $\psi(c) = \sum (a_{ij} \cdot \exists_z + b_{ij} \cdot \exists_j)_{j = 1,2, ..., m, z = 1,2, ..., k}$.

(11)

The presented provisions show that the working process taking place in the engine and the structural parameters of its mechanisms have the greatest impact on changing the engine parameters. But since the operating parameters depend on the design features, it can be assumed that the optimal impact, allowing to change the technical and operational characteristics of the engine, will be a change in the design parameters of the mechanisms. Since the main working process takes place in the engine cylinder, the details of the cylinder-piston group will have the greatest impact on the change in the engine output parameters [1, 2].

Then, the output stream of workflow parameters can be expressed by a system of equations:

\[
A = \begin{pmatrix}
\eta_V &= f(P_p, P_o, T_r, \rho_o) \\
N_i &= f(\eta_i, \eta_V, \rho_o) \\
N_e &= f(N_i, \eta_m) \\
\eta_i &= f(P_i, V_h, Q_t) \\
\beta_i &= f(H_w, \eta_i) \\
\beta_e &= f(H_w, \eta_o, \eta_m)
\end{pmatrix},
\]  

(12)

where $\eta_V$ - filling ratio; $P_p$ - pressure at the end of the intake stroke, MPa; $P_o$ - environmental pressure, MPa; $T_r$ - residual gas temperature, °C; $\rho_o$ - density of fresh charge at the inlet, g/cm³; $N_i$ - indicator power, kW; $\eta_i$ - indicator efficiency coefficient; $N_e$ - effective engine power, kW; $\eta_m$ - mechanical efficiency coefficient; $P_i$ - average indicator pressure of the actual cycle, MPa; $V_h$ - working volume of one cylinder, l; $Q_t$ - amount of heat supplied with fuel per cycle, kJ; $H_w$ - calorific value (net calorific
value) of fuel (kJ/kg); $g_i$ - specific indicator fuel consumption, g/kW·h; $g_e$ - specific effective fuel consumption, g/kW·h.

It is known that indicator efficiency coefficient, specific indicator fuel consumption, effective efficiency coefficient, and specific effective fuel consumption depend on the filling ratio. The effective power and specific fuel consumption will depend on the mechanical efficiency coefficient, which is determined by the mechanical losses in the engine, in particular in the CPG.

Therefore, a change in the charge density, taking into account a decrease in mechanical losses due to a decrease in the friction coefficient in the CPG, will allow changing the technical and operational and fuel and energy parameters of the internal combustion engine [9].

In accordance with the information model of the influence of engine parameters on the performance of the vehicle, the parameters of the output flow can also be represented by a system of functions:

$$
y = \begin{cases}
g_s = f(g_{ee}, N_{ee}, v, \rho_f) \\
l_a = f(N_{ee}, M_k) \\
D = f(N_{ee}, M_k, v) \\
C = f(Q_{f}, H_s, N_{ee}, v) \\
\end{cases}
$$

(13)

where $g_s$ - road fuel consumption in kg/100 km; $g_{ee}$ - operational specific effective fuel consumption, g/kW·h; $N_{ee}$ - engine operating power, kW; $v$ - vehicle speed, km/h; $\rho_f$ - fuel density, g/l.

Based on the foregoing, we can propose the following conceptual model of the relationship and impact of the modernization of the cylinder-piston group on the technical and economic performance of engines and operational performance of the vehicle (Figure 3).

A change in the filling ratio can be carried out without changing the design parameters of the air supply system by increasing the amount of fresh charge. Without resorting to mechanical devices (compressors), this can be realized only by lowering the charge temperature. Since when a fresh charge enters the cylinder, it is heated from the parts of the combustion chamber, one of the solutions to this will be to lower the temperature of the details. Of all the parts of the CPG, the piston has the highest temperature, naturally it is the source of maximum heating of the fresh charge, therefore, to implement the solution, it is necessary to lower its temperature during operation. This can be realized by forming a heat-insulating coating on the bottom or head of the piston [10–12].

An increase in power and a decrease in specific fuel consumption is possible, again, without a design change, by a reduction in mechanical losses in engine mates. Since the largest losses occur at the CPG, in particular at the friction pair “piston ring-cylinder liner”, the direction of reduction of mechanical losses will be a decrease in the friction coefficient in the considered conjugation. In this case, one of the solutions is to apply antifriction materials to the working surfaces of parts. Moreover, based on the classical theory of tribo-technology, the most effective will be the application of an anti-friction coating over a large area of friction. In this case, the largest area is the working surface of the cylinder liner. The solution of this problem can be carried out by forming on the working surface the liner coatings with high antifriction properties. Given the working conditions of the CPG parts and the properties of their materials, the anti-friction coating should have properties close to the details [1–7].

3. Results of the research and discussion

The practical implementation of the proposed model consisted in the formation of a heat-insulating coating on the bottom and piston head by the method of microarc casing and the application of an antifriction layer on the working surface of the cylinder liner by the introduction of copper inserts.
Moreover, the mathematical model for calculating the operational performance of vehicles from the parameters of the formed coatings was implemented numerically using a combination of finite difference methods and finite elements. Using the experimental planning methods, the initial model was reduced to an empirical-statistical one.

For this, two series of numerical experiments were used with the original model when varying the values of coatings (thickness, microhardness, thermal resistance, friction coefficient, etc.) in structurally-technologically acceptable ranges.

Detailing the conceptual model allows to create the optimal scheme for achieving the goal (Figure 4)
The calculation results showed that a decrease in the temperature of the oxidized piston bottom leads to an increase in the density of the incoming air charge, and therefore, the filling coefficient by 3.1%, the friction coefficient in the pair "piston ring - cylinder liner" decreases by 1.8 times. Accordingly, the friction power of rings decreases from 5.02 to 2.87 kW, and the total power of mechanical losses in an engine equipped with experimental CPGs decreases by 11.6%.

The results of a theoretical calculation of operational indicators show that equipping an experimental CPG with pistons with an oxidized bottom and a metallized working surface of the cylinder liners of the UMZ - 417 engine will make it possible to increase the indicator engine efficiency by 4.6%. The mechanical efficiency of the engine increases from 0.789 to 0.831 (by 5.9%). Effective efficiency (due to an increase in indicator and mechanical efficiency) increases from 0.22 to 0.25 (by 13.6%). The exhaust gas content of carbon monoxide and hydrocarbons decreased by 8% and 11%, respectively. The directional fuel consumption, depending on the transmission and vehicle speed, is reduced by 5.1 - 7.9%. The dynamic characteristic of the vehicle, depending on the transmission, improves by 5.1 - 7.9%. The acceleration - by 5.4-6.3%. The convergence of fuel economy indicators obtained by calculation and experimentally is 90 - 93%.

An example of mathematical modeling to establish the interdependence of vehicle performance on engine parameters proves that, in accordance with the presented methodology, relationships can be built up with other indicators, for example, traction properties on parameters of transmission units, dynamic characteristics on layout decisions, body aerodynamics, etc.

4. Conclusion

The use of mathematical modeling allows us to develop a concept for improving the operational performance of a vehicle, to optimize the process of choosing ways to upgrade the engine and vehicle. Using the proposed model of the interdependence of performance indicators on materials and geometric parameters of units and mechanisms will reduce time and labor costs when designing a new and
modernizing the existing types of engines and vehicle models, to eliminate erroneous design solutions, to reduce the time from the start of design to the mass production of vehicles and engines.

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