The regression model of automated control of timely replacement of air diesel air filter

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Abstract. The article analyzes the literature sources and experience of four-year operation of the diesel locomotive of series 2TE116UM No. 016 on the Ulan-Bator railway (Mongolia). The results of the analysis show that the turbocharger does not exhaust its service life until regular preventive maintenance, due to the onset of such a phenomenon as surging, stability of its operation is disrupted. It has been established that the main causes of surge emergence are: flow stall from the diffuser walls, and/or from the guide vanes, and/or from the impeller blades and others. These deviations from the operating conditions are caused by various factors, the main among which is the contamination of the air filter. The dynamics of the onset of surging, the inspection and the replacement of the air filter are analyzed. An empirical dependence of the air flow on the degree of pressure increase in the turbocharger is obtained. In order to automate the control of the turbocharger's unattended operation in the diesel locomotive operation mode set by the controller, the dependences of the pumping distance on the ambient temperature, the degree of pressure increase and the pressure at the inlet of the turbocharger, depending on the degree of air filter contamination, were investigated. The source data from the controller was processed in the Statgraphics Plus package and adequate regression equations were obtained to determine the running period magnitude before the surge start from each parameter individually and from the combined effect of all parameters. The coefficients of determination of the regression dependencies obtained are 92-99%.

1. Introduction
The mathematical analysis of experimental data with their subsequent approximation is of great importance for the development of automated processes of controlling the functioning of complex systems. The approximation with simultaneous statistical data processing is often provided by regression analysis methods [1]. Out of the entire set of functions depending on the input variables and external influences, only the regression function has a minimum forecast error of the output variable of the object under study. For that reason, regression models are widely used in various industrial, economic and educational systems [1-8]. The development of regression models helps to avoid an exhaustive search of options in the design and selection of optimal operating modes of equipment and processing procedures through the use of information technologies. A good enough approximation to the real process requires the use of a more complex multivariate regression model, which we will consider below.
2. Turbocharger surge dynamics, inspection and filter replacement graphs

During the operation of diesel locomotives, diesel air filters are gradually contaminated. With that, their passage area decreases, which leads to a decrease in air flow through the diesel [9-10]. The discharge characteristic shifts to the lower flow zone, the temperature of the exhaust gases rises. An increase in gas temperature can not compensate for a decrease in gas air flow; therefore, the speed of the turbine and compressor is reduced. As a result of increasing the boost pressure, the air consumption decreases, and the joint operation mode of the turbo-charger and the engine moves to a point at another hydraulic characteristic located closer to the surge limit.

The change in air flow through the engine leads to a change in the indicator efficiency and engine shaft speed. With that, the efficiency of the turbocharger also changes, which affects the efficiency of the engine cycle.

If to maintain a constant frequency of rotation of the diesel shaft by increasing the fuel supply when the air filters are contaminated, this will result in an even greater increase in the temperature of the exhaust gases. In this case, the flow characteristics of the diesel engine and the line of operating modes of the turbocharger will be located closer to the surge limit [11].

Works [12-16] evaluated the impact of reducing the boost pressure on the output parameters of a diesel locomotive engine, as well as the effect of the degree of pollution of air filters on the constancy of performance of a diesel locomotive turbocharger.

The results of the operational data analysis showed that the turbocharger service life does not become exhausted until regular preventive maintenance, because stability of its operation is disrupted due to the onset of surging.

![Figure 1](image1.png)

**Figure 1.** The dynamics of the onset of surging during the run $L_s$.

![Figure 2](image2.png)

**Figure 2.** The dynamics of carrying out the inspection of air filter during the running period of the diesel locomotive $L_i$. 
Figure 3. The dynamics of replacing the air filter.

It is established that the main causes of surge occurrence are: flow stall from the walls of the diffuser, and / or from the guide vanes, and / or from the vanes of the impeller; as well as instability of the flow in a vaneless space; self-oscillations of air in the "compressor - blow-off-and-boosting receiver" system. These deviations from the operating conditions are caused by various factors, the main among which is the contamination of the air filter.

As can be seen from Fig. 1, surging occurred in 0.5-3 months after the inspection of the air filter, in 4.5-6.5 months after replacing the filter.

To prevent the occurrence of surging, the workers of the Ulan-Bator Railway tried to carry out the inspection as often as possible (Fig. 2), or to replace the air filter of a locomotive, which led to heavy material expenditures.

To identify the quantitative effect of the technological parameters of a diesel locomotive’s turbocharger on the running period at which surging occurs, and to develop empirical models for the automated control of safe running period, statistical processing of the experimental data has been performed using the Statgraphics Plus package.

Let us denote the following: \( T \) is the ambient air temperature, °C; \( p_z \) is the pressure in front of the turbocharger, Pa; \( \pi_k \) is the degree of pressure increase; \( G \) is the air consumption, kg/s. With increasing running period \( L \) of the diesel locomotive, the hydraulic resistance of the air filter increases due to contamination and the value of \( p_z \) increases. To prevent surging, the filter is to be replaced or inspected, during which it is subjected to cleaning. This results in a decrease in the value of \( p_z \). Therefore, the distance of run of the locomotive \( L_{rp} \), at which surge occurred, was calculated by the formula

\[
L_{rp} = L - L_f
\]  

where \( L \) - from the beginning of operation, km, \( L_f \) is the running period during which the filter was inspected or replaced.

The air flow depends on \( \pi_k \) and is described by linear regression (2), see Fig. 4. The regression validity coefficients (2): the coefficients of determination \( R^2 \) and of Darbin-Watson \( DW \), mean square \( \sigma \) and absolute \( \Delta \) errors are listed in the table.

\[
G = -0.9188 + 2.2345\pi_k
\]

Figure 5 shows a comparison of the experimental data of \( G_e \) with the calculation results of \( G_c \) by formula (2). The regression validity coefficients (2) are listed in the table.

Studying the influence of each parameter separately on the value of the safe running period, we obtained one-dimensional regressions, the reliability coefficients of which are given in the table.

The dependence of \( L_{rp} \) on \( T \) is quadratic (see Fig. 6).
Figure 4. Dependence of the air flow $G$ on the degree of pressure increase $\pi_k$ in the turbocharger.

Figure 5. Comparison of values calculated by formula (1) $G_c$ with experimental values $G_e$.

Figure 6. Dependence of surge running period on air temperature.

The greatest value of $L_{rp}$ can be found from the necessary condition for the maximum function:

$$\frac{\partial L_{rp}}{\partial T} = 1674.98 - 2 \cdot 152.46 \cdot T = 0 \rightarrow \max L_{rp}$$

At $T = \frac{1674.98}{304.92} = 5.49 \, ^\circ\text{C}$

The regression validity coefficients (3) are shown in the table. The accuracy of the regression found can be judged by Fig. 7, which compares the running period values calculated by formula (3) $L_{crp}$ (abscissa axis) with experimental $L_{rp}$ (ordinate axis).

$$L_{crp} = 106674.0 - 1674.98T - 152.46T^2$$

(3)

Figure 7. Comparison of the values of $L_{crp}$ calculated by formula (3) with experimental $L_{rp}$.

The dependence of $L_{rp}$ on $\pi_k$ is parabolic (see Fig. 8). The regression validity coefficients (4) are
presented in the table.

\[ L_{rp} = -5.130 \cdot 10^6 + 3.810 \cdot 10^6 - 693361.0 \pi_s^2 \]  \hspace{1cm} (4)

\[ \pi \]

Figure 8. The dependence of \( L_{rp} \) on \( \pi_s \).

From the necessary condition for the existence of an extremum of the function, we find that the greatest value of \( L_{rp} \) is achieved when \( \pi_s = 2.747 \), because

\[ \frac{\partial L_{rp}}{\partial \pi_s} = 3809610.0 - 2 \cdot 693361 \cdot \pi_s = 0 \rightarrow \max L_{rp} \]

At \( \pi_s = \frac{3809610}{1386722} = 2.747 \) °C

The accuracy of the regression found can be judged by Fig. 9, which compares the running period values calculated by formula (4) \( L_{crp} \) (abscissa axis) with experimental \( L_{rp} \) (ordinate axis).

Figure 9. Comparison of the values of \( L_{crp} \) calculated by formula (4) with experimental \( L_{rp} \).

\[ L_{rp} = -2.91352 \cdot 10^6 + 39.29 \cdot p_z - 0.00013 p_z^2 \]  \hspace{1cm} (5)

\[ \pi \]

Figure 10. Dependence of \( L_{rp} \) on \( p_z \).
The regression validity coefficients (5) are listed in the table. Fig. 11 shows a comparison of the running period values calculated by formula (5) \( L_{crp} \) (abscissa axis) with experimental data \( L_{rp} \) (ordinate axis).

The fourth compatibility condition for the valve SJ:

\[
L_{crp} = -43418.4 + 43607.8 \cdot \pi_k^2 - 1.172 p_z - 154.837 T^2
\]  

Table 1. Regression validity coefficients.

| Formula No. | \( R^2, \% \) | \( DW \) | \( \sigma \) | \( \Delta \) |
|-------------|----------------|--------|----------|--------|
| (2)         | 99.99          | 2.74   | 0.0156   | 0.0113 |
| (3)         | 92.16          | 1.54   | 11392.60 | 10859.30 |
| (4)         | 99.67          | 1.45   | 2917.77  | 21744.0 |
| (5)         | 98.46          | 1.45   | 6181.34  | 19119.70 |
| (6)         | 96.99          | 3.26   | 7231.95  | 4331.31 |

The obtained equation (6) will allow controlling the amount of safe running period during operation of the locomotive, which should not exceed the value of \( L_{rp} \) obtained by formula (6) and accurately describes 99.26% of the initial data.

The accuracy of the regression found can be judged by Fig. 9, which compares the running period values calculated by formula (6) \( L_{crp} \) (abscissa axis) with experimental \( L_{rp} \) (ordinate axis).

Thus, the obtained multi-parameter linear regression was used in the development of an automated software module [17, 21-29] that monitors the running period of a diesel locomotive and prevents surging as a result of timely replacement of the air filter.
Figure 12. Comparison of the values of $L_{crp}$ calculated by formula (6) with experimental $L_{rp}$.

3. Conclusion

The use of automated calculation systems can significantly reduce the time to solve the problem. The programming functions built into the system make it possible to create simple program modules necessary for repeated calculations, for example, to find the coordinate $x_{max,o}$ and the radius $r_{max,p}$, used in further calculations as the initial approximation for the $Given$ – $minimize$ computational unit.

The built-in Given block allows solving the problems of exploring functions for an extremum ($Given$ – $minimize$, – $maximize$, – $minerr$, etc.), however, it is limited by initial approximations, which in most cases leads to incorrect results. The main advantage of the Given block, in this case, is the ability to calculate rational geometric parameters of the seat (thickness) by solving an optimization problem with constraints on allowable stresses.

The presented example of solving the problem of optimizing the geometric dimensions of a thin-walled seat under dynamic and static loading in PTC MathCAD, its automation using the built-in Given block can also be supplemented with data obtained from modeling in various systems (MSC.vN4W, APM WinMachine, etc.).

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