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Planning of a Numerical Experiment in Order to Determine the Effect of Operating Factors on the Traction-Adhesion Properties of Locomotives

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The paper reviews the results of an evaluation of the influence of the operating factors on traction-adhesive proper-ties of a locomotive. Planning of an xperiment was performed for two locomotives – freight locomotive 2TE116 and shunting locomotive TEM103. The input for performing the numerical experiment was variation of 6 factors: the change in the wheel diameter of the first wheelset due to wear, the change in the mass of the locomotive as a result of the change in the amount of the fuel as well as the wheel rims wear, the impact of the friction damper in the primary suspension, change in the primary and secondary suspension stiffness due to operation. Regression equati-ons were obtained in code and natural form, which describe the effect of operating factors on the coefficient of utilization of the locomotive adhesion mass.

Keywords: Coefficient of Adhesion Utilization, Experiment Planning, Regression Equations

1 Introduction

To evaluate the influence of operating factors on traction properties of locomotives, the method of the theory of experiment planning [1-4] was used, which allows to significantly reduce the number of investigated states and obtain a mathematical model of the monitored process, to evaluate the overall as well as the individual influence of each factor on the draw force . The experiment planning method assumes selection of factors, their value and the interval of variation, determination of the system response, planning matrix assembly and obtaining the regression equations [5-8].

2 Selected numerical experiment factors

Based on the analysis of the studies [9-15], the following factors were used to perform the numerical experiment: the change in wheel diameter of the first wheelset due to wear, the change in mass of the locomotive as a result of the change in fuel amount and the wear of the wheel rims, the influence of the primary suspension friction damper, the change in stiffness of the primary and secondary suspension stifness due to operation. The calculations were made for the six-axle freight locomotive 2TE116 and the four-axle locomotive type TEM103.

The secondary suspension of the TEM103 shunting locomotive has an increased stiffness of 45 kN/mm [9]. According to the static modeling results, it was evaluated that the stiffness of such a value does not affect the coefficient of adhesion utilization. Therefore, in case of the shunting locomotive, this factor has not been taken into account. Based on the analysis of the impact of the friction dampers located in the primary suspension system of the type 2TE116 locomotive, it was found that it comes to suspension blocking and thus the locomotive's coefficient of adhesion utilization is significantly reduced. When designing the TEM103 shunting locomotive, the primary suspension was designed more rationally using hydraulic dampers. Therefore, when planning a numerical experiment for the given locomotive type, the blocking of the suspension was not considered. The number of factors for freight locomotive 2TE116 remained 6, for shunting locomotive 4.

3 Planning the numerical experiment

Each factor can take one or several values, levels in the experiment. The number of experiments N necessary to realize all possible combinations and factor levels can be determined by:

$$N = U^k \text{ [-]}, \tag{1}$$

Where:
U – number of levels [-],
k – number of factors [-].

To get both models, we choose two levels. Then, during an experiment involving all factors, it is necessary to inves-tigate a number of states $N = 2^6 = 64$ to obtain the 2TE116 freight locomotive model. In case of the TEM103 shunting locomotive, it is $N = 2^4 = 16$ states. The number of investigated conditions in the experiment involving all factors con-siderably exceeds the amount of mathematical model coefficients. In other words, an experiment involving all the factors has a certain redundancy of the investigated conditions. When the number of factors is greater than 4, significant time losses occur when performing the experiment. It is therefore appropriate to reduce the number of investigated states based on the information which is of little importance for building a model. Such a decision can be made by using regular partial replicas of the experiment involving all factors including a suitable number of investigated conditions, preserving the basic properties of the planning matrix. A replica, involving only half of the investigated states, is called a half-replica. In this situation, a half-replica is used, so the number of the investigated states for the determination of the influence of operating factors on the coefficient of adhesion utilization of the freight locomotive 2TE116 is reduced to 32.

The main designation of the varying variables is shown in Tab. 1.

***Tab. 1** Limit values of the varying parameters*

Parameter	Locomotive type	
	TEM103	2TE116
Weight of wheelset [kN]		
x_{1max}	20.51	17.7
x_{1pr}	19.01	16.23
x_{1min}	17.5	14.76
Weight of fuel [kN]		
x_{2max}	553.87	863.3
x_{2pr}	529.25	813.03
x_{2min}	504.62	762.75
Stiffness of the primary suspension [kN/mm]		
x_{3max}	2.0	2.0
x_{3pr}	1.9	1.9
x_{3min}	1.8	1.8
Stiffness of the secondary suspension [kN/mm]		
x_{4max}	-	11.0
x_{4pr}	-	10.4
x_{4min}	-	9.8
Radius of locomotive wheel [m]		
x_{5max}	0.525	0.525
x_{5pr}	0.5215	0.5215
x_{5min}	0.518	0.518
Friction damper friction force [kN]		
x_{6max}	-	8.0
x_{6pr}	-	4.0
x_{6min}	-	0

The output of the numerical experiment is the maximum coefficient of the adhesion weight utilization η, x_1, x_2, x_3 formalized or coded factors determined by relation:

$$x_1 = \frac{x_i - x_{ipr}}{x_{i\max} - x_{ipr}} = \frac{x_i - x_{ipr}}{x_{ipr} - x_{i\min}}, \quad (2)$$

Where:

$x_{i\,pr} = (x_{i\,max}, - x_{i\,min})/2$,

$x_{i\,max}$, $x_{i\,min}$ – limit values of variation of independent variables (factor quantities).

In a coded system based on a relation (2), they will respect the assumption:

$$x_{i\min} \rightarrow x_i = -1; \quad x_{ipr} \rightarrow x_i = 0; \quad x_{i\max} \rightarrow x_i = 1, \quad (3)$$

The interdependence of factors is described by pairs of interdependent factors x_1x_2, ..., x_nx_m, and triples $x_1x_2x_3$ ..., $x_nx_mx_k$. The total amount of all possible effects, including the free member of the regression equation b_0, linear effects and relationships of all classes are equal to the amount of investigated states of the experiment involving all factors. The number of possible dependencies of the selected number of classes is determined by the relation [2]:

$$C_k^m = \frac{k!}{m!(k-m)!}, \quad (4)$$

Where:

m – number of elements in an interdependent relationship [-],

k – number of factors [-].

Thus, the 2TE116 freight locomotive experiment plan includes 15 pairs of interdependent parameters and 20 triples of interdependent parameters. The TEM103 shunting locomotive experiment plan contains 6 pairs and 4 triples of parameters. Task solving, i. e. determination of the dependence of the maximum adhesion weight utilization on the observed factors was obtained in the form of the expression:

$$y = f(x_1, \ldots, x_k), \quad (5)$$

Where:

f – response function,

x_1, x_2 – factors,

$y = \eta$.

To obtain the numerical experiment plan, a starting point (base level or start level) around which the test points are located symmetrically with respect to the zero level. The results for the investigated state with a selected set of factors allow us to create a model that can be used to determine values at other points of the factor space. When planning the experiment, it is necessary to consider the interdependence of pairs and triples of factors. Searching for a mathematical model begins with consideration of possible states of the monitored system. In accordance with the normalization characteristic of the plan matrix of the experiment including all factors, the relation for the delimitation of coefficient values of the regression equation is written in the form [16]:

$$b_i = \sum_{i=1}^{N} \frac{x_{ji} y_i}{N}, \quad (6)$$

Where:
f – response function,
x_1, x_2 – factors,
$y = \eta$.

4 Research results

Based on the relation (6), the values of regression coefficients are determined. Since the regression equations are obtained by performing a numerical experiment, with all calculations done by the computer program Experiment Planning for Railway Transport (Certificate No. 31722 of 21. 01. 2010) [17] created by the authors, the values of the output quantity – the coefficient of adhesion weight utilization η have no quantification errors. All coefficients of the regression equations have importance (except zero ones), and thus the regression equations are adequate to the calculated inputs obtained. The resulting output values calculated by the regression equations (y) and the values obtained previously according to the mathematical methodology of delimitation of η (y*) are fully matched.

The value η in the center of the plan for 2TE116 equals 0.79875, the value of the free member of the regression equation is 0.79875. The value η in the center of the plan for TEM103 is 0.86075, the value of the free member of the regression equation is 0.86075. Thus, the regression equations adequately describe the monitored process. The coefficient of regression equation of the coefficient of adhesion utilization of the freight locomotive 2TE116 from the operating factors in coded form has the form:

$$\begin{aligned}\eta = {} & 0.79875x_o + 0.005937x_1 + 0.009125x_2 + 0.00281x_3 + 0.002437x_4 - 0.0115x_5 + 0.008187x_6 - \\ & + 0.0001875x_1x_2 + 0.0001875x_2x_3 - 0.0005x_2x_5 + 0.000125x_1x_5x_6.\end{aligned}, \quad (7)$$

To convert the regression equations from the coded system to the natural form, the transition formula (2) is used. By substituting the expressions in tab. 1 and by using relation 2, the regression equation 7 acquires the resulting form:

$$\begin{aligned}\eta = {} & -2.514 + 0.0188m_d + 0.00164m_p - 0.00585c_I + 0.0041c_{II} + 5.99R + 0.0533F_t - \\ & + 0.00000254m_dm_p - 0.0243m_dR + 0.00136m_dF_t + 0.000037m_pc_I - 0.000285m_pR -, \\ & + 0.0985RF_t + 0.00069m_dRF_t.\end{aligned} \quad (8)$$

Where:
m_d – weight of the first wheelset,
m_p – weight of fuel,
c_I – stiffness of the primary suspension,
c_I – stiffness of the secondary suspension,
R – radius of the locomotive wheel,
F_t – friction damper friction force.

The regression equation for the coefficient of adhesion utilization of the shunting locomotive TEM103 from the oprating factors in the coordinate form is:

$$\eta = 0.86075x_o + 0.0055x_1 + 0.004x_2 + 0.00025x_3 - 0.0005x_4 - 0.00025x_1x_2 + 0.00025x_1x_2x_3. \quad (9)$$

The resulting equation for the TEM103 shunting locomotive:

$$\begin{aligned}\eta = {} & -0.582 + 0.075m_d + 0.0027m_p - 0.681c_I - 0.143R - 0.000135m_dm_p + \\ & + 0.0357m_dc_I - 0.00128m_pc_I + 0.0000675m_dm_pc_I.\end{aligned} \quad (10)$$

The obtained regression equations (8) and (10) allow to evaluate the influence of locomotive parameters on the η changes in the process of operation.

The resulting negative effect from all factors for the 2TE116 freight locomotive is set at 8.5% and 2.4% for the TEM103 shunting locomotive. The influence rate of each factor on the resulting parameter (η) was determined by means of numerical pair correlations (τxy) [18]. The results are shown in the diagram in Fig. 1, showing that the most negative impact on the locomotive TEM103 is shown by a pair of effects of weight change of the wheelset and the change in the weight of the car body due to the change in weight of the fuel mass. For locomotive 2TE116, it is a change in wheel diameter due to wear.

The inadequacy of the coefficient of adhesion utilization against the expected values is proposed to be compensated by adding a bogie loading device located between the case and the bogie. The effectiveness of the solution is confirmed by increase in the coefficient of adhesion utilization to 6.8%. As the vertical load on the wheelsets in the operating process changes, the load force of the loading device should vary between 2% for TEM103 locomotives and 6% for 2TE116 locomotives.

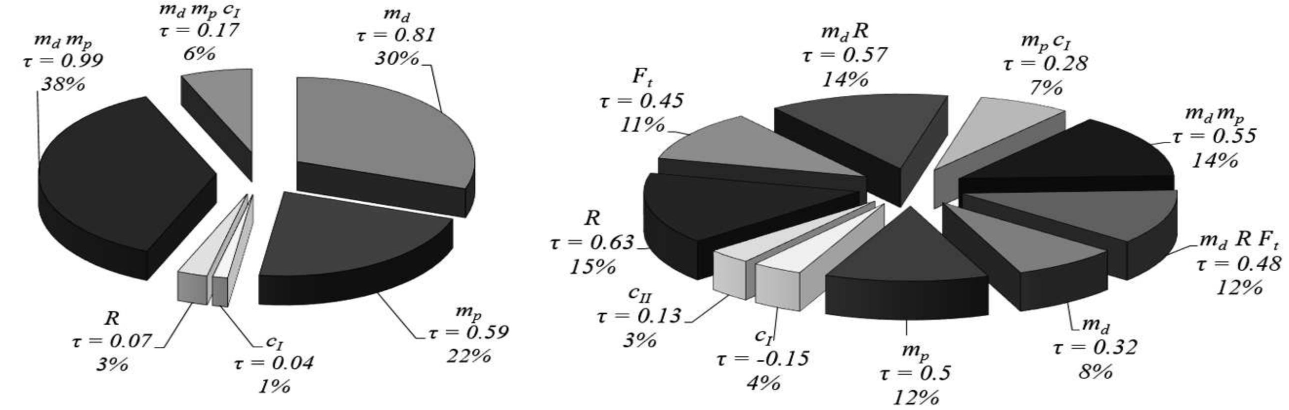

Fig. 1 *The operational factor influence on the traction properties of locomotive a) TEM103, b) 2TE116*

5 Engineering design

The results of the research have shown that when using pneumatic cylinders in the form of loading devices, it is possible to obtain relatively easily the desired value of the coefficient of adhesion utilization. To solve the problem of equalizing the wheelset load on a modern TEM103 locomotive, manufactured in Luhanskteplovoz, a.s. [19], a patented loading device was used to increase the efficiency of maximum draw power (Fig. 2).

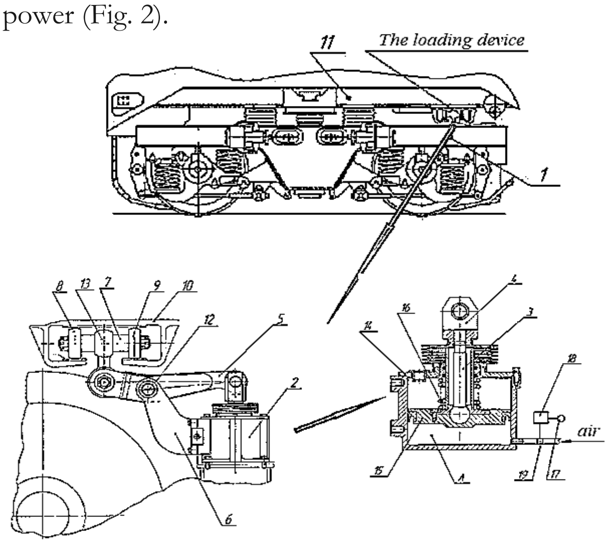

Fig. 2 *Schema of loading device placed on the TEM103 shunting locomotive bogie*

The loading device is attached to the locomotive bogie frame 1. When moving the locomotive from place, the loading device switches on using the "increase adhesion" button located on one of the control panels. At this time, air under pressure of 0.4 MPa is supplied to the cavity A (Fig. 2) of the cylinder 2 with the lid 14. Piston 15 is pushed upwards by the rod 3, the recoil spring 16 is compressed. The lever 5, rotatably mounted on the axle 12 by means of the rod 13 and the rollers 8, 9 rests on a guide 10 welded to the frame 11 of the locomotive car body. When further pushing the piston 15, the force from the rod 3 via the fork 4, the lever 5, the axle 12 and the bracket 6 with the suspension 7 is transmitted to the crossbeam of the bogie frame 1 and thus increases the wheelset load on the respective side of the crossbeam.

When the determined speed of the locomotive is reached, the control unit 18, coupled with the speedometer 17, comes into operation. Air is drained from the cavity A of the cylinder 2 via the electro-pneumatic valve 19 and the pis-ton 15 returns to the starting position by the action of the return spring 16.

6 Conclusion

The redistribution of the vertical load from the wheelsets to the rail affects negatively the traction properties of a locomotive. The assumption of the static load of the wheelsets is not fulfilled. Loads diverge from theoretical values, which is associated with various design and operational factors.

- A methodology has been developed to identify the coefficient of adhesion utilization η of six-axle and four-axle locomotives that considers the impact of differences in wheel diameters, the change in weight of a wheelset in the operaing process, wear, car body weight change due to fuel weight change, locomotive balance, friction force of the primary suspension, stiffness of the primary and secondary suspension system.
- The negative impact of the friction dampers on the traction properties of the locomotives increases proportionally with the increase in the friction force of the damper. Therefore, for the TEM103 shunting locomotive, a rationalization measure of replacing the friction dampers of the primary suspension for hydraulic ones was designed and implemented.
- It has been found that one of the effective methods of increasing the coefficient of adhesion utilization is the use of a bogie loading

device allowing for an increase of η by 6,8%. In the process of operation, locomotive parameters are changed, which requires the loading force of the device to be controlled within 2% for TEM103 locomotives and 6% for 2TE116 locomotives.

- A perspective design of a loading device has been developed to increase the coefficient of adhesion utilization.

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