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# Increase in the Technical Level of Mine Haul Trucks

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**Abstract.** The study presents theoretical and methodological fundamentals of minehaul trucks optimal design. It provides methods based on the systematic approach to integrated assessment of truck technical level and methods for optimization of truck parameters depending on performance standards. The results of these methods application are given.

## Introduction

Technical re-equipment of open-pit mining facilities and further development and upgrades of automotive mining machinery are inextricably linked. Efficiency in execution of hauling operations determines the technical and economic performance indicators of coal production on the whole, as transportation costs make up more than 50% of the overall mining costs.

So far skyrocketing payload capacity as the main tendency for mining automotive machinery development has not been accompanied by a corresponding gain in performance and increase in other figures of merit. However, it should be noted that the engineering policy meant to boost the payload and aimed at further mining truck redesign without major quality changes is outdated. The evolution of mining haul trucks and empirical approach to their design will never result in any quality breakthroughs in the future. At the same time power-to-weight ratio of the new wheeled mine transport is to be increased together with its reliability, service life and performance; empty mine haul truck weight is to be lowered; all truck parameters are to be balanced. Open-pit mining transport enhancement can be achieved, in the first place, by optimal tuning of all the structural components, units and systems of a truck not only among themselves, but with the facility environment as well. So, when designed, a mine haul truck must be regarded as a complex technical aggregate being in its turn a part of the total surface mining transport system.

These areas are closely connected with the problem of improvement in the industrial output quality, which, being a part of the widely spread in the Western world “total quality control” ideology, is one of the major issues for the Russian economy.

Vast amounts of mined bulk to be transported by haul trucks, influence of hauling operations upon the speed of open-pit mining and their high labour intensity stimulate the constant search for large-scale improvements to the mining transport.

M.V. Vassiliev, A.A. Kuleshov, M.G. Potapov, K.N. Trubetskoy, S. Alarie, M. Gamache [1], C.N. Burt, L. Caccetta [2, 3], R.A. Carter [4, 5], V.A. Temeng [6, 7] and others contributed greatly to the theory and practice of automotive mine machinery usage at open-pit facilities. In their papers, they determined the sphere of haul truck efficient use in open-pit mining [1, 3, 5, 8-10], summed up the experience of its operation [2, 4, 7, 11-14], highlighted the issues of techno-economic studies devoted to automotive mine machinery usage efficiency [1-7, 15-17].

Belarusian Automobile Plant(OJSC «BELAZ», Republic of Belarus)is a major world manufacturer of heavy dump trucks used in mining and construction. Mainly its produce consists of mine dump trucks with a payload capacity of 30 to 360 t. During all the years (since 1948 when the company was founded) BelAZ specialists have been doing their best to improve the truck designs. These designs implementations contributed to providing mining companies with high-performance equipment.

However, in recent years BelAZ designing engineers have had to face the following problem: increased payload did not lead to the proportional rise in truck performance. The power-to-weight ratio is still insufficient, the payload ratio and life mileage are too low as well as the truck technical level in general and only production and maintenance costs go up with every passing year.

This situation can be accounted for by the fact that the theory of mining machinery optimal design (including mine dump trucks) has not been developed sufficiently yet. Mine haul truck design framework still needs the procedures for ultimate solutions synthesis. The systematic approach as a basis for this synthesis has actually not been used for BelAZ dump trucks design and their parameters optimization until recently.

**Results and discussion**

In order to estimate the technical level and quality of the mining machinery (including automotive machinery) adequately, the most agreeable alternative is the non-expert assessment method, which allows assessing functionally homogeneous machines of various types, models and modifications [1]. For this purpose, be the technical level we mean the truck quality at the stage of development of the design assignment.

According to the systematic approach, the functional criterion as the basis of this method appears to be the product of the truck performance $\Pi_T$ by the specific energy of the mined bulk $W$ transportation:

$$\lambda = W \cdot \Pi_T. \tag{1}$$

The specific energy of transportation can be calculated according to the correlation deduced by the authors (kJ/t·km):

$$W = \frac{g[f_c + i_{max}(2k_T + 1)]}{\sqrt{1 + i_{max}^2}}, \tag{2}$$

where$f_c$ – coefficient of rolling resistance for a truck on the road; $i_{max}$– possible slope for a truck to ride on; $k_T = m_a/m_{gr}$ – payload ratio ($m_a, m_{gr}$ – truck payload and empty weight, t); $g$–gravity acceleration, m/s$^2$.

When assessing the technical level of the existing trucks and designing new ones in order to determine the functional criterion one should use the theoretically calculated performance values. Besides, for comparable results the influence of the payload upon the functional criterion is to be excluded, that is why it is reasonable to use 1 auto-ton performance (or truck specific performance) (t·km/ t·h):

$$\Pi_{T_y} = 0.56 N_{eng}^{ud}(1 + k_T)\frac{\sqrt{1 + i_{max}^2}}{g[i_{max} + f_c(2k_T + 1)]}, \tag{3}$$

where $N_{eng}^{ud} = N_{eng}/(m_a + m_{gr})$ – power-to-weight ratio of the engine (power-to-weight ratio of the truck), kW/t.

The final dependence for the functional criterion calculation is as follows (kW/t):

$$\lambda = 0.56 N_{eng}^{ud}(1 + k_T)\frac{f_c + i_{max}(2k_T + 1)}{i_{max} + f_c(2k_T + 1)}. \tag{4}$$

Another important issue of the assessment is the grounded selection of the parameters determining the technical level of haul trucks to have the essential and sufficient nomenclature made up. The parameters that determine the technical level to the most are selected from the initial nomenclature after a thorough analysis of the operational processes followed by a further verification of their matching (direct correlation) and representativity (the degree of influence upon the technical level depending, in its turn, on the purpose of its assessment). Eventually the following system of the parameters was obtained (Fig. 1).

The given parameters can be determined at the earliest stages of truck design. In compliance with the qualimetry principles extra parameters can be introduced depending on the specific conditions and demands. The integrated assessment of the technical level is carried out by means of unique ($q_{ij}$) and generalized ($k_i$) parameters according to the formulae of the method [1].

The developed method allows not only assessing the truck technical levels but also choosing the most promising models with its help and providing quantitative evaluations of the decisions to be madeat the design stage.

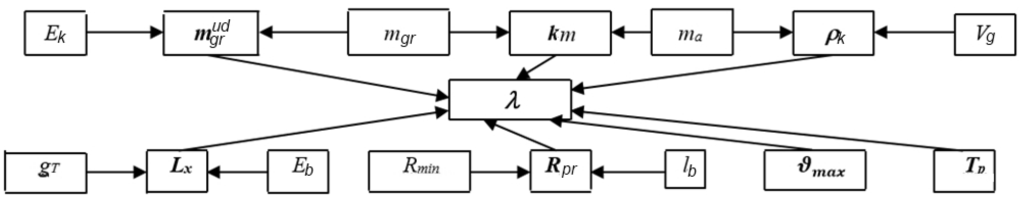


Fig. 1. Complex of haul trucks technical level parameters $\lambda$– functional criterion, kW/t; $m_{gr}^{ud} = m_{gr}/E_k$ – truck specific payload, t/m$^3$; $k_m = M/m_b$ – truck weight coefficient (comparative materials consumption); $\rho_k = m_a/V_g$ – component density, t/m$^3$; $L_x = 100E_b/g_T$ – distance to empty, km; $R_{pr} = R_{min}/l_b$ – specific turn radius; $\vartheta_{max}$– maximum speed of the truck, km/h; $T_p$ – predetermined service life (truck mileage), km; $m_{gr}$ – truck payload capacity, t; $E_k$ – body capacity, m$^3$; $m_a$ – truck curb weight, t; $V_g$ – total truck volume (product of length by width and height), m$^3$; $E_b$ – fuel tanks capacity, l; $g_T$ – linear fuel consumption, l/100 km; $R_{min}$ – minimum turn radius, m; $l_b$ – truck wheel base, m; $M = m_a + m_{gr}$ – gross weight, t; $m_b = (0.212N_{eng} - 8.4)$ – truck weighted average mass (corresponding to the installed engine capacity $N_{eng}$)

In the paper according to the selected parameters, a comparative assessment of 22 trucks was made, 14 of which are BelAZ products, 4 – of Caterpillar, 1 of Komatsu and 1of Unit Rig. This group comprises the whole range of truck payloadcapacities(30 to 320 t). The trucks are compared in similar conditions.

After the generalized parameter of the truck technical level was calculated and analyzed it can be concluded that for all the 22 trucks this parameter exceeds 0.5 (Fig. 2), therefore, this result proves that the technical level of all the trucks is quite high.

The average technical level for all the machines in question is 0.695. Also, it should be noted that the level of BelAZ trucks and that of the trucks produced by foreign companies are virtually the same. The average value of the technical level generalized parameter for the trucks considered is 0.698 and that is only 0.7% higher than for BelAZ trucks, which means that as far as the vehicle structure perfection and new design ideas and solutions are concerned Belarusian Plant products show very little difference.

The results of the unique parameters calculations allow stating that BelAZ trucks surpass their counterparts in 4 parameters out of seven, namely in truck specific payload $m_{gr}^{ud}$ (6.4% higher), component density $\rho_k$ (11.2%), truck weight coefficient (comparative materials consumption) $k_m$ (9.8%) and specific turn radius $R_{pr}$ (8.7%); also BelAZ trucks are behind in distance to empty $L_x$ (6.7% lower), maximum speed of the truck$\vartheta_{max}$ (8.7%) and especially in predetermined service life (truck mileage) $T_p$ (27.5%).

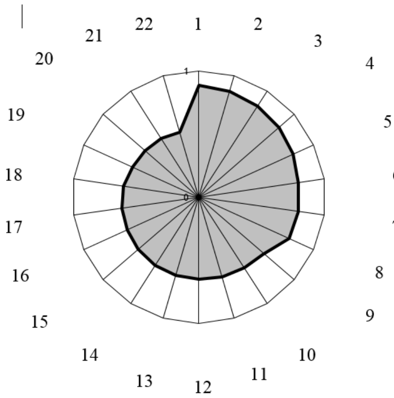


Fig. 2. The generalized parameter of the trucks technical level (in the brackets - the parameter value k)

On the basis of the analysis it can be concluded that power-to-weight ratio of new vehicles is to be increased, empty weight is to be lowered while reliability and service life are to be raised to a higher level; all truck parameters are to be balanced and reviewed as interrelated and interdependent. All this shows that the systematic approach to new wheeled open-pit mine machinery design is essential.

At the present moment, there is a distinctive deficiency of guidance materials and norms and specifications that could standardize products optimal design as an important stage of quality improvement. Systematic approach is to be regarded fundamental for optimal design as it allows perceiving the vehicle as a whole while its individual elements are being designed. The systematic approach to a vehicle parameters determining consists of the following: firstly, every parameter must correlate optimally with the others, and secondly, output operational performance established on the basis ofthese parameters is to comply with the specified values.

It is suggested that the mathematical model of truck parameters optimization should be presented as a set of regression analysis equations directly connecting output operational performance and the parameters which are to be optimized.

Haul truck as a system is characterized by its own structure and parameters. The truck structure predetermines its elements and their interrelationships; it is to ensure the truck optimal functioning and for this purpose the parameters characterizing the truck are to be optimized. It is reasonable to use generalized evaluations of the technical level as optimization criteria and its unique indicators as optimized parameters. Such approach enables to reduce the problem dimensions, to simplify its solution and also to ensure objective assessments of the suggested solutions.

After carrying out the analysis of the output operational performance (such as payload ratio $k_T$ and 90% predetermined service life (truck mileage) $T_p$) specified in the regulations (including interstate GOST 30537-97) and specific truck performance $\Pi_{T_y}$ as the main technical and operational parameter for mining haul trucks and taking into account their interrelationships(dependence (3) the essential and sufficient nomenclature of the optimized parameters was compiled. It is stated in Fig. 3.

The problem of finding out how much each of these parameters influences the technical level of the generalized parameter chosen as the optimization criterion and subsequent generating an objective function model on this basis is a problem of approximation type and can be solved with the help of the theory of experiment design [6, 7]. Having been carried out, the correlation analysis of the interrelationships between the parameters that are to be optimized determined the degree of their independence (Table 1**)** and allowed diminishing their number from 8 (Fig.3**)** to 3 ($N_{eng}^{ud}$,$k_T$ and $T_p$).

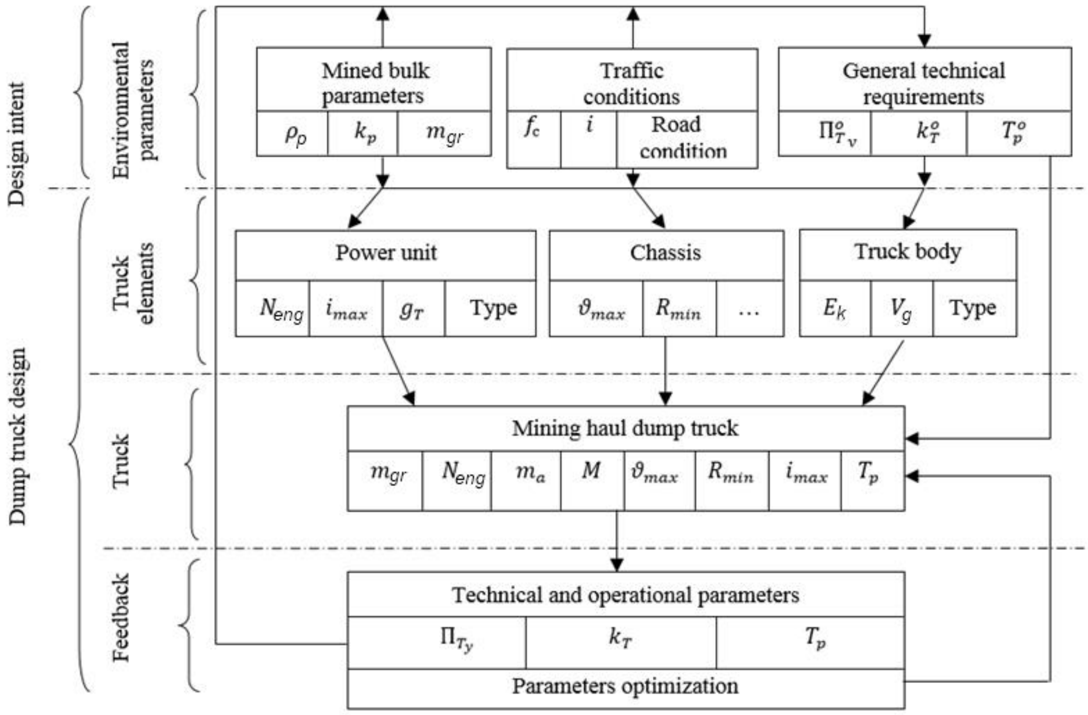


Fig. 3. Flow chart for haul truck design and truck parameters optimization ($\boldsymbol{\rho}_{\text{п}}$ – minedbulkdensity; $\boldsymbol{k_p}$ – mined bulk loosening factor)

Table 1.Results of the correlation analysis of the truck parameter inter relationships

| **Model** | **Regression parameters** | | **Regression parameter value, $F$** | **Fisher criterion critical value, $F_{\text{кр}}$** | **Correlation index, $r$** | **Correlation index reliability, $t$** | **Student's t-test critical value, $t_{\text{кр}}$** |
|---|---|---|---|---|---|---|---|
| | ***a*** | ***b*** | | | | | |
| $N_{eng} = a + bm_{gr}$ | 70.9 | 7.950 | 1097.1 | 3.49 | 0.984 | 24.7 | 2.086 |
| $M = a + bN_{eng}$ | −8.40 | 0.212 | 1659.0 | 3.49 | 0.990 | 31.4 | 2.086 |
| $\vartheta_{max} = a + bN_{eng}$ | 61.6 | $-8.7 \cdot 10^{-3}$ | 784.4 | 3.49 | 0.695 | 4.32 | 2.086 |
| $R_{min} = a + bM$ | 9.0 | 0.017 | 1588.3 | 3.49 | 0.919 | 10.4 | 2.086 |
| $g_T = a + bN_{eng}$ | –9.10 | 0.434 | 1384.8 | 3.49 | 0.988 | 28.6 | 2.086 |
| $i_{max} = a + bN_{eng}$ | 0.294 | $-6.3 \cdot 10^{-3}$ | 181.8 | 3.49 | 0.604 | 3.39 | 2.086 |
| $i_{max} = a + bk_T$ | 0.870 | –0.848 | 121.4 | 3.55 | 0.555 | 2.98 | 2.101 |
| $k_T = a + bm_{gr}$ | 0.657 | $1.04 \cdot 10^{-3}$ | 1031.5 | 9.55 | 0.890 | 3.38 | 3.182 |
| $T_p = a + bm_{gr}$ | 0.378 | $0.82 \cdot 10^{-3}$ | 660.6 | 19.0 | 0.959 | 4.79 | 4.303 |

When solving the problem of truck parameters optimization, the following constraints can be found.

1. Constraints on compliance of the output operational performance parameters $\Pi_{T_y}$, $k_T$, $T_p$ with $\Pi^o_{T_y}$, $k^o_T$, $T^o_p$ regulated by GOST 30537-97 (Fig. 3). The models of these constraints as well as the objective function model are formulated afterthe mathematics experiment by which we mean that the technical level generalized parameter $k$ and the output operational performance parameters are calculated upon the condition of specific combinations of variables according to the experiment design matrix.

2. Constraints on the ratio of the $k_T$, $T_p$ parameters to the truck payload capacity $m_{gr}$. The given interrelationships are shown in Table 1.

3. The boundary conditions describing the range of variations for the optimized parameters. The analysis shows that the only boundary condition that can be established for all these parameters is non-negativity ($N_{eng}^{ud} \geq 0$; $k_T \geq 0$; $T_p \geq 0$).

Eventuallya mathematical model for the optimization (MMO) of technical level parameters and truck parameters was derived which is a linear programming problem.

$$\begin{cases} k = a_0 + a_1 N_{eng}^{ud} + a_2 k_T + a_3 T_p \rightarrow max; \\ a_{11} N_{eng}^{ud} + a_{12} k_T + a_{13} T_p \geq \Pi_{T_y}^{o} - S_0^{\Pi} - a_{10}; \\ a_{11} N_{eng}^{ud} + a_{12} k_T + a_{13} T_p \geq \Pi_{T_y}^{o} + S_0^{\Pi} - a_{10}; \\ a_{21} N_{дв}^{уд} + a_{22} k_T + a_{23} T_p \geq T_p^0 - S_0^T - a_{20}; \\ a_{21} N_{eng}^{ud} + a_{22} k_T + a_{23} T_p \geq T_p^0 + S_0^T - a_{20}; \\ a_{31} N_{eng}^{ud} + a_{32} k_T + a_{33} T_p \geq k_T^0 - S_0^k - a_{30}; \\ a_{31} N_{eng}^{ud} + a_{32} k_T + a_{33} T_p \geq k_T^0 + S_0^k - a_{30}; \\ N_{eng}^{ud} \geq 0; k_T \geq 0; T_p \geq 0, \end{cases} \quad (5)$$

The evolved method is based upon the technical requirements regulated by GOST 30537-97 but it can be used for the purpose of optimization of haul truck parameters and other external conditions established by the customers. The method suggests a complete rethink of the establishment of critical parameters for truck specifications.

For the purpose of establishing parameters of the objective function model and constraints a mathematics experiment was carried out according to the Full Factorial Experiment $2^3$ plan. Asaresult, a MMO was developed as follows:

$$\begin{cases} k = -0.422 + 0.172 N_{eng}^{ud} - 0.043 k_T + 0.391 T_p \rightarrow max; \\ 0.715 N_{eng}^{ud} + 9.077 k_T \geq 9.818; \\ 0.467 N_{eng}^{ud} + 9.077 k_T \leq 9.900; \\ 0.065 N_{eng}^{ud} - 1.250 k_T \geq -0.605; \\ 0.065 N_{eng}^{ud} - 1.250 k_T \leq -0.289; \\ 0.051 N_{eng}^{ud} - 0.195 k_T - T_p \geq -0.338; \\ 0.051 N_{eng}^{ud} - 0.195 k_T - T_p \leq -0.090; \\ N_{eng}^{ud} \geq 0; k_T \geq 0; T_p \geq 0. \end{cases} \quad (6)$$

The experiment confirmed linearity of the objective function models and all the constraints. The linearity is conditioned by the fact that all interrelations between the generalized and unique parameters of the technical level and between the truck parameters can be viewed as linear with a reasonable degree of accuracy as suggested by regression parameters high values and correlation indices reliability (Table 1).

At the same time, the analysis of the objective function model allows drawing the conclusion that the higher are the values of power-to engine ratio $N_{eng}^{ud}$ and predetermined service life (truck mileage) $T_p$ and the lower is payload ratio $k_T$, the higher the technical level generalized parameter (optimization criterion) $k$.

At that the optimal solution of the system will be the following combination of the optimized parameters and optimization criterion value:

$$N_{eng}^{ud*} = 8.308 \text{ kWt/t}; \; k_T^* = 0.663 \text{t/t}; \; T_p^* = 0.633 \text{ mln. km}; \; k^* = 1.227, \quad (7)$$

thus, for the technical level generalized parameter to reach its maximum, power-to-weight ratio is to be increase and make up no less than 8.3 kWt/t; payload ratio is not to exceed 0.660; 90% truck mileage is to be at least 630 thous. km. All this allows increasing the technical level by 38.5% in comparison with the best dump truck from the group under consideration and by 76.5% when compared to the group on average.

After the model (6) analysis the optimal values for power-to-engine ratio $N_{eng}^{ud*}$, payload ratio $k_T^*$, predetermined life service (truck mileage) $T_p^*$ and the technical level generalized parameter $k^*$(7) were obtained.These composite indices can be synthesized into particular optimal parameters which are included into a truck specification. Optimal parameters synthesis is based on ensuring optimal functioning of a truck as a whole with due consideration of the existing interrelationships between these parameters.

**Conclusion**

The analysis of the conditions and practices in mining machinery operation enabled us to ascertain that the composition of BelAZ truck fleet is of relatively low quality. At present, the number of guidance papers and materials for mine trucks adequate assessment and recommendations aimed at their technical level increase is not sufficient.

Integrated comparative assessment of the technical level of mining machinery produced by both domestic and foreign manufacturers highlighted the prospect of the technology advances in mining machinery and their implementation as early as the design stage. Increase in the technical level of newly developed mining automotive machinery can be achieved through the usage of theoretically grounded methods of optimal design which allows balancing all parameters.

Optimal design is based upon the optimization mathematical modeling of machinery operations and parameters. The objective function and constraints of the optimization mathematical model are viewed as a set of regression analysis equations which connect corresponding figures with the optimized parameters directly. It is suggested to use the technical level generalized parameters as an optimization criteria and its unique indicators as optimized parameters.

Implementation of scientific methodological and technical recommendations will allow bringing newly developed mine machinery up to the level that matches world standards.

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