UDC 622.684

Effective Power and Speed of Mining Dump Trucks in Fuel Economy Mode

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Existing methods for determining the effective power, based on the calculation of the average indicator operation of the engine during the piston stroke, do not take into account the change in thermodynamic parameters and the polytropic operation of the engine, the value of which depends on the polytropic efficiency of the duty cycle. This is the reason that the calculation of the effective power leads to some error – the margin of the engine features. The identification of this stock allows us to review the entire line of dump trucks in the direction of increasing their passport effective capacity, which will lead to a reduction in capital purchase costs due to the choice of a previously underestimated and cheaper option, as well as a reduction in current operating costs due to a decrease in the specific fuel consumption rate. Taking into account the stochastic nature of the transport process and assessing the influence of all external and internal factors when calculating the rational mode of operation of a mining truck can further reduce specific fuel consumption by choosing the rational speed of its movement in loaded and empty directions.

Key words: effective power; traction and speed characteristics; polytropic efficiency; specific fuel consumption; dump truck speed

How to cite this article: Alexandrov V.I., Vasilyeva M.A., Koptev V.Y. Effective Power and Speed of Mining Dump Trucks in Fuel Economy Mode. Journal of Mining Institute. 2019. Vol. 239, p. 556-563. DOI: 10.31897/PMI.2019.5.556

Introduction. Analysis of the state of the energy efficiency of transport systems in mining enterprises shows that the main parameters that determine the energy characteristics of transport work are high-speed modes of movement of mining dump trucks and resistance to movement on career roads. Resistance and speed are directly related to the power consumed for transporting the rock mass and, accordingly, to the available power of the truck engine, the value of which determines the specific energy consumption (diesel fuel) in a given speed mode of the truck [1, 2].

Methodology. Within the study of high-speed modes of movement of dump trucks, three main methods are used:

• theoretical, establishing a functional relationship between the forces of resistance to movement, speed of movement and power consumption;

• experimental, based on an array of experimental data obtained in the course of measurements directly at the mining enterprise;

• comprehensive, combining theoretical and experimental approaches to determining the speed regimes of mining dump trucks.

A feature of these methods in the study of the speed of dump trucks is that the main factors affecting the speed are mining conditions, i.e. external characteristics of the transport process. The internal characteristics of the dump truck engine are not considered in the considered methods. At the same time, such quantities as effective engine power, effective specific fuel consumption, engine traction and speed characteristics and other effective parameters characterizing the mechanical and energy properties of a diesel engine of a mining dump truck and being a function of the effective (disposable) power of the dump truck are not considered.

Adaptation of the internal parameters of the dump truck engine to external parameters determined by mining and technical conditions is the main factor in the possible increase in the operational and energy efficiency of mining dump trucks.

Mproving the efficiency of internal combustion engines (ICE) remains one of the most important problems of modern engine building. The solution to this problem is directly related to an increase in the effective (available) engine power and a decrease in the specific consumption of diesel fuel, i.e. increasing fuel efficiency of engines in various load conditions. For the first time, a description of the working process (cycle) occurring in the cylinder of a reciprocating internal com-

DOI: 10.31897/PMI.2019.5.556

bustion engine (ICE) was given by G.Gildner, then developed by V.I.Grinevetsky, N.R.Brilling, E.K.Masing, A.S.Orlin, M.G.Kruglov and other scientists.

Discussion. At the design and calculation stage of internal combustion engines, the main effective parameters are determined. These parameters include: effective power N_e; effective efficiency η_e, specific fuel consumption g_e, effective torque M_e. The classical approach to determining these characteristics is based on determining the average indicator pressure from the indicator diagram p, i.e. pressure, which acting on the piston in one working stroke from the top dead center (TDC) to the bottom dead center (BDC), does the work equal to the useful work for the entire working cycle of the internal combustion engine.

As can be seen from the definition of the average indicator pressure, the calculation of the internal combustion engine does not take into account the non-uniformity of pressure along the piston, since in reality the gases expand and the pressure drops. In addition, the calculations assume that the rotation of the crankshaft occurs at a constant frequency. In reality, the rate of change of the volume of gases in the engine cylinders, i.e. the piston speed is variable, and in TDC and BDC it is generally zero. As a result, we conclude that the use of an average indicator pressure, convenient to simplify the calculations, leads to significant errors in understanding the internal combustion engine and the nature of the processes occurring in the cylinders of thermodynamic processes. To bring the calculations to acceptable accuracy in the classical approach, when performing calculations, a large number of empirical coefficients are used that are determined during bench tests, which, in essence, is a way of «fitting» theoretical calculations to parameters characterizing actual phenomena during the operation of ICE [3, 5, 9].

In diesel engines operating on a mixed cycle, the useful work is equal to the difference in the expansion and compression work. The expansion work consists of the preliminary expansion work and the expansion work at the maximum temperature of the combustion products. An analysis of the compression work and the preliminary expansion work shows that their value is almost the same (Fig. 1), i.e. the work of the preliminary expansion is compensated by the work of compression, since these works have opposite signs:

$$L_{\text{pol}} = L_{4-5} - L_{1-2} + L_{3-4}, \tag{1}$$

or, if accepted $L_{1\text{-}2} = L_{3\text{-}4}$, than

$$L_{\text{pol}} = L_{4-5}, \tag{2}$$

where $L_{4\text{-}5}$ – combustion expansion work; $L_{1\text{-}2}$, $L_{3\text{-}4}$ – accordingly, work in the compression process and the work of preliminary expansion.

From here we come to the conclusion: any modern diesel engine has reserves for increasing power and reducing specific fuel consumption. A certain reserve of power and effective engine efficiency lies in the need to consider the polytropic nature of gas expansion in working cylinders, taken into account by polytropic efficiency, which characterizes the deviation of the actual process of gas expansion from an ideal, adiabatic process.

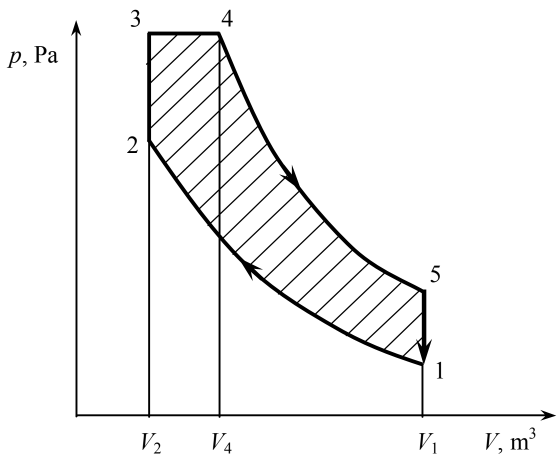

Fig.1. PV-ICE diagram with mixed heat supply process

1-2 – adiabatic compression; 2-3 – heat input at motionless position; 3-4 – adiabatic expansion; 4-5 – heat removal; 5-1 – compression

The well-known effective engine power formula is written as follows:

$$N_e = \frac{p_i V_h i n}{120} \eta_{\text{mech}}, \tag{3}$$

where p_i – average pressure indicator; V_h – cylinder volume; i – number of cylinders; n – crankshaft velocity; η_{mech} – mechanical efficiency.

 DOI: 10.31897/PMI.2019.5.556

The value p_iV_i determines the average specific work of the combustion products of diesel fuel in the engine cylinders, which varies in magnitude and direction. The specific fuel consumption expressed in terms of the average specific work will also be an average value depending on the position of the piston in the engine cylinders,

$$g_e = 3600\frac{G_f \cdot 120}{p_iV_i in}\eta_{mech}, \quad (4)$$

where G_f – fuel consumption, kg/s.

From formula (3) it can be seen that an increase in the effective power leads to a decrease in the specific consumption of diesel fuel and an increase in the fuel efficiency of the truck engine.

In the formula (3), the value p_iV_i defines some indicator work in the engine cycle:

$$p_iV_i = L_i = Amz_{av}R\Delta T,$$

where L_i – indicator of work in a cycle; A – coefficient of proportionality, taking into account the irreversibility of real processes of the engine cycle, is determined by the efficiency: mechanical (η_{mech}) and polytropic (η_{pol}); $m = V_h\rho_g$ – gas mass in the engine cylinder; ρ_g – gas density; z_{av} – the degree of compressibility of real gases (combustion products of diesel fuel) depends on the critical values of pressure and temperature of the gas mixture; $R = \mu R/\mu_g$ – gas constant of gases (fuel combustion products); $\Delta T = T_2 - T_1$ – temperature difference; T_2 и T_1 – temperature at the beginning and at the end of the thermodynamic process.

As a result, formula (3) of the effective power was written as:

$$N_e = N_i\eta_{mech} = n_{pe}\frac{mz_{av}R(T_2 - T_1)\, in}{120}\eta_{mech}, \quad (5)$$

where $n_{pe} = \frac{k-1}{k}$ – pseudoentropes indicator; k – adiabatic indicator.

The value η_{mech} determines the overall engine efficiency η_{en}, which depends on polytropic efficiency

$$\eta_{en} = \eta_e\eta_{pol}, \quad (6)$$

where $\eta_e = \frac{N_e}{G_fQ_b^p}$ – effective efficiency power; Q_b^p – bottom heat of combustion; $\eta_{pol} = \frac{1}{n_{be}}\frac{\lg\varepsilon}{\lg\tau}$ – polytropic efficiency; $\varepsilon = \frac{p_2}{p_1}$ – compression ratio; $\tau = \frac{T_2}{T_1}$ – temperature characteristic in the polytropic process of expansion of diesel fuel combustion products.

The engine efficiency formula is written as follows

$$\eta_{en} = \eta_e\eta_{pol} = \frac{n_{be}V_h\rho_r z_{av}RT_1(\tau-1)in}{120G_fQ_b^p}\eta_{mech}\frac{\lg\varepsilon}{\lg\tau} = n_{be}\frac{k' z_{av}RT_1(\tau-1)}{G_fQ_b^p\eta_{mech}}\eta_{pol} = \frac{k'k_f}{G_fQ_b^p}, \quad (7)$$

where $k_{th} = n_{be}z_{av}RT_1(\tau-1)\eta_{pol}$ – thermodynamic coefficient characterizing the specific thermal work of the engine in polytropic compression – expansion processes; $k' = \frac{V_h\rho_m in}{120}\eta_{mech}$ – engine design parameter.

A feature of formula (7) is the presence of a polytropic efficiency value that takes into account the deviation of the theoretical adiabatic (isentropic) expansion process from the actual polytropic process. In addition, it follows from formula (7) that the efficiency of the engine and its effective power are determined mainly by the temperature range during the expansion of the combustion products of diesel fuel.

 DOI: 10.31897/PMI.2019.5.556

Theoretical dependences show that the energy characteristics of a diesel engine cycle are largely determined by the temperature conditions of polytropic expansion processes and the value of thermodynamic characteristics, which is a function of temperature and polytropic process efficiency. The value of the thermodynamic characteristics mainly depends on the thermodynamic properties of the working fluid, combustion products of diesel fuel and, in particular, on the gas constant R and, accordingly, on the molar mass and composition of the gas mixture. For the types of liquid diesel fuel accepted in practice, the gas constant value is determined by the perfection of the processes of mixture formation, the coefficient of excess air and temperature conditions of the diesel engine cycle. It is characteristic that the thermodynamic characteristic does not depend on the volume of the cylinders [6, 7, 10].

By comparative numerical calculations of the working pressure in the engine cylinders and, accordingly, the effective power for the BelAZ-7540 dump truck, performed according to the classical method and the developed method, it was found that the latter, taking into account the polytropic nature of the expansion of combustion products, leads to high pressure values and effective power in comparison with the traditional method of determining these quantities:

$$p_i = \frac{p_a \varepsilon^{n_1}}{\varepsilon - 1}\left[\lambda(\rho - 1) + \frac{\lambda\rho}{n_2 - 1}\left(1 - \frac{1}{\varepsilon^{n_2 - 1}}\right) - \frac{1}{n_1 - 1}\left(1 - \frac{1}{\varepsilon^{n_1 - 1}}\right)\right] =$$

$$= \frac{0.1 \cdot 12^{1.35}}{12 - 1}\left[2{,}5 \cdot (1{,}2 - 1) + \frac{2.5 \cdot 1.2}{1.3 - 1} \cdot \left(1 - \frac{1}{12^{1.3-1}}\right) - \frac{1}{1.35 - 1}\left(1 - \frac{1}{12^{1.35-1}}\right)\right] =$$

$$= 0.26 \cdot (0.5 + 5.25 - 1.66) \cdot 10^5 = 1.06 \ \text{MPa}, \quad (8)$$

where p_a – initial cylinder pressure; ε – compression ratio; n_1 – polytropic index during compression; λ – degree of pressure increase; ρ – degree of pre-expansion; n_2 – polytropic indicator in the process of expansion;

$$p_c = n_{be}\rho_f z_{av} R T_5 (\tau - 1) = \frac{1.4}{1.4 - 1} \cdot 10 \cdot 0.9 \cdot \frac{8314.3}{180} \cdot (1910 - 1014) = 1.31 \ \text{MPa}. \quad (9)$$

Relative pressure increase

$$\Delta p_1 = \frac{p_c - p_i}{p_c} \cdot 100 = \frac{1.31 - 1.06}{1.31} \cdot 100 \ \% = 19.01 \ \%. \quad (10)$$

The effective power equal to the product of pressure on the volumetric flow rate of the working fluid increases by the same 19.01 %. This increase is provided by the energy reserve, determined by taking into account the polytropic nature of the compression process – expansion of the working fluid in the cylinder of a diesel engine.

Thus, each diesel engine has an unaccounted for power reserve, and the resulting pressure increase (10) must be considered as a power reserve coefficient.

Engine power is a function of the specific resistance to movement (dynamic factor) of a dump truck along quarry tracks, the traction force applied to the wheels of the dump truck, the mass of the cargo carried and the transportation speed, which together determine the specific fuel consumption per unit load. Moreover, for each fixed value of variable factors, the speed of movement, and, consequently, the specific fuel consumption, take the only value corresponding to the given size of the dump truck [11].

To optimize the energy parameters of the dump truck, we calculate the minimum fuel consumption per unit of transported cargo for a given capacity of the dump truck body. Minimize function

DOI: 10.31897/PMI.2019.5.556

$$E = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} T\Omega G_{ij}}{\sum_{i=1}^{m} Q_i}, \qquad (11)$$

where T – the number of hours of the truck for the year; Ω – total number of travels in empty and loaded directions in one hour; G_{ij} – fuel consumption per travel; Q_i – annual loading capacity.

The determining parameter of model (11) is the speed of the dump truck, since the specific fuel consumption and the number of trips that a dump truck can make per unit time depend on this parameter.

When deriving the equations for the speed of the dump truck in the cargo and empty directions, we proceeded from the definition of the dynamic factor, i.e. specific resistance to the movement of the dump truck on career roads. The dynamic factor is the most important parameter of the truck, the value of which depends on the mass of the transported cargo (cargo or empty direction of movement), the traction force applied to the wheel of the truck, and depending on the overcome resistivity, the speed of the truck [12-15].

The traction force of a dump truck is expressed as the sum

$$F_{\text{wh}} = \sum W_{\text{wh}}, \qquad (12)$$

where $\sum W_{\text{wh}} = W_0 + W_i + W_R + W_{\text{air}} + W_j$ – total resistance to movement (main, from the road gradient, on curved sections, air, inertia).

From formula (12) we obtain the well-known formula for the dynamic factor:

$$D = \frac{F_{\text{wh}} - W_{\text{air}}}{G_{\text{a}} g} = w_0 \pm w_i + w_R + w_j, \qquad (13)$$

where w_0, w_i, w_R, w_j – resistivities (main, from the road gradient, on curved sections and inertia forces).

The traction force applied to the wheels of the dump truck is described by the functional

$$F_{\text{wh}} = f(G_{\text{a}}, D, v_{\text{en}}) \qquad (14)$$

or since F_{wh} has its own meaning for each size of the truck, it can be written

$$F_{\text{wh}} = f(D, v_{\text{en}}), \qquad (15)$$

Thus, functional (14) decomposes into two functions:

$$\frac{F_{\text{wh}}}{v_{\text{en}}} = f_1(D), \qquad (16)$$

$$F_{\text{wh}} = f_2(v_{\text{en}}). \qquad (17)$$

Expressions (16) and (17) can be explicitly written as power monomials, i.e.

$$\frac{F_{\text{wh}}}{v_{\text{en}}} = k_1 = k_2 D^{\alpha_1} \text{ и } F_{\text{wh}} = k_3 v_{\text{en}}^{\beta_1}, \qquad (18)$$

where $k_1 = F_{\text{wh}}/v_{\text{en}}$ – specific force; $k_2 = e^{\alpha_0}$, $k_3 = e^{\beta_0}$ – proportionality factors (numbers); e – base of the natural logarithm; α_0, α_1, β_0, β_1 – degree indicators characterizing the intensity of change in traction F_{wh}.

After simple transformations of formulas (18), we obtain the following expression for the speed of the truck:

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$$v_{\text{en}} = \frac{k_3^n}{k_2^m D^j}, \tag{19}$$

where $n = \dfrac{1}{1+\beta_1}$; $m = \dfrac{\beta_2}{\beta_1(1+\beta_1)}$; $j = \dfrac{\alpha_1}{1+\beta_1}$.

The values in the formula (19) are determined on the basis of experimental data obtained from the analysis of the operation of mining dump trucks. For each size of the truck, the values of the degree indicators have their own value, depending on the operating conditions of the transport system. It follows from formula (19) that the speed of dump trucks is a complex parameter that depends on many factors, in particular, on the specific work performed in the transportation work process (denominator). With an increase in specific work, the speed of movement, both in the loaded and in the empty directions, decreases. In the empty direction, the specific work has a minimum value, therefore, the speed of movement takes the greatest value under the same conditions as in the first case. The denominator in formula (19) characterizes the intensity (speed) of the implementation of traction by a dump truck with a change in speed.

Formula (19) expresses the main dynamic characteristic of the truck's working process (along with the dynamic factor), since the formula includes almost all the parameters (kinematic, dynamic and energy) that determine the operation of dump trucks during their operation in specific mining and geological conditions. Theoretical determination of the coefficients and exponents is probably a very difficult task. There is considerable practical experience in operating dump trucks in open pits and opencast mines, which will make it possible to apply the statistical method of analyzing experimental data to obtain regression equations based on the least squares method.

The experimental graphical dependences of the traction force and speed on the mass of the transported cargo for the BelAZ-7540 dump truck are shown in Fig.2 [4].

Using the method of regression analysis, by processing the experimental data of the BelAZ-7540 dump truck, a generalized formula for the speed of its movement is obtained:

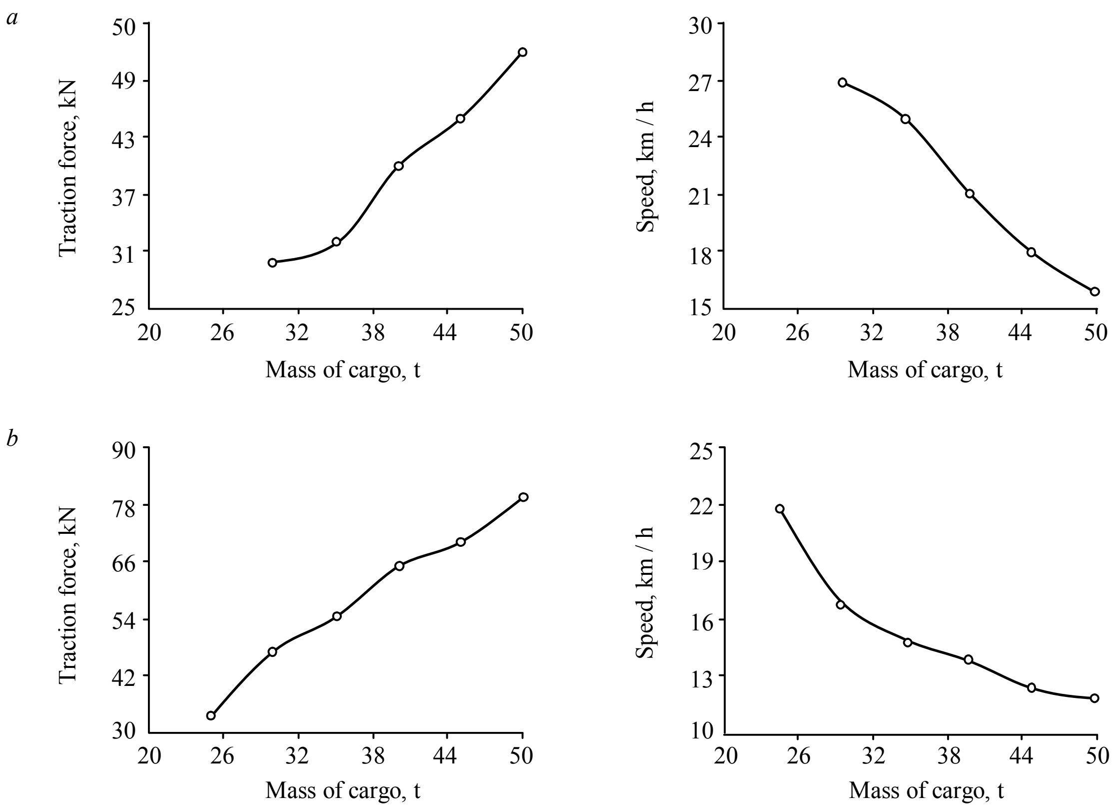

Fig.2. Dependencies of the traction force and the speed of the truck on the mass of the transported cargo:
a – experimental data at D = 1000 N/t; *b* – at D = 1450 N / t

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$$v_{\text{en}} = \frac{252.77 - 0.111 D^{0.437} G}{D^{0.314}}. \quad (20)$$

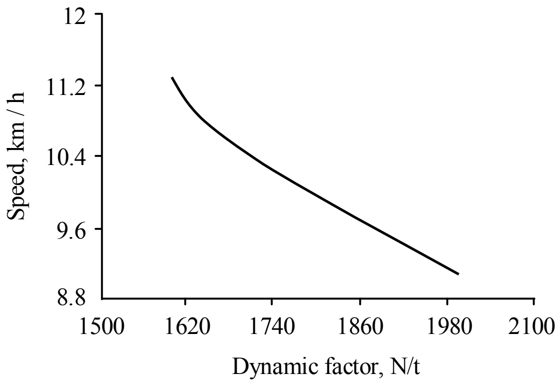

Fig.3. Change in speed when changing the dynamic factor (specific resistance to the movement of the dump truck)

The specified values in formula (20) are the mass of the transported cargo and the calculated value of the dynamic factor, which depends on the specific resistance to movement of the truck. Formula (20) shows that with an increase in the dynamic factor, the speed of the truck decreases. The nature of the change in speed can be shown for the case of a constant mass of cargo G with a change in factor D.

Figure 3 shows a graph of the speed of movement of a loaded BelAZ-7540 dump truck as a function of dynamic factor D. The graph shows that with an increase in specific resistance to the movement of the dump truck, but in fact a dynamic factor, the speed decreases, this is confirmed by experimental data.

Since the dynamic factor takes into account the traction force, the minimum necessary to overcome all resistance to movement, we can assume that each value of the dynamic factor corresponds to its own value of the speed of movement, and this value will be optimal. Therefore, when moving at this speed, the specific fuel consumption function will take a minimum value at a known loading capacity.

In the work, a career route consisting of two sections was calculated, and optimal values of the speed of movement for each section (see table) in loaded and empty directions were obtained.

Dynamic performance of the BelAZ-7540 dump truck

Section	Dynamic factor, N/t	Speed, km/h	Traction force, kN
1	845.6 / 745.0	17.0 / 18.5	42.2 / 21.6
2	798.0 / 456.0	25.3 / 31.6	46.3 / 23.7

Note. In the numerator, indicators for the loaded direction, in the denominator for empty.

Based on the obtained speed values, an operational calculation of the quarry was made and the optimum value of specific fuel consumption for this route was obtained [8].

Conclusions

1. The currently used methods for selecting a dump truck are based on indicator power, which does not take into account the thermodynamic processes of polytropic compression and expansion processes at all. In order to make the calculation results more accurate, in addition to the design parameters, it is necessary to take into account the thermodynamic ones, such as the temperature at the beginning of the polytropic expansion cycle, the gas constant of the fuel-air mixture, as well as the polytropic efficiency, which will take into account the deviation of the actual compression processes-extensions from adiabat. The calculations made for the BelAZ-7555 mining dump truck showed that the effective engine power is 19.01 % more than stated in the passport. This increase is provided by the energy reserve, determined by taking into account the polytropic nature of the compression process – expansion of the working fluid in the cylinder of a diesel engine.

2. Based on experimental data on the actual values of specific resistance to the movement of dump trucks, the optimal speeds of the dump trucks were established and justified as a function of traction, dynamic factor and the mass of the transported cargo.

DOI: 10.31897/PMI.2019.5.556

3. The analysis of experimental data showed that with an increase in the mass of the transported cargo and an increase in the dynamic factor, and in fact, specific resistance to the movement of the truck, the speed decreases and the traction increases. So at a maximum value of the transported cargo of 30 tons, the speed of movement has the lowest value at all possible resistivities. The greatest value of the speed of movement is observed during the movement of an empty dump truck, when the resistance to movement and traction force have the least value.

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The article was received on 23 Yanuary, 2019.
The paper was accepted for publication on 27 May, 2019.