



Integrated Energy-Specific Method for Calculating Fuel Consumption of Mining Haul Trucks Considering Transport Cycle Structure

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Abstract

The accuracy of calculating diesel fuel consumption by mining haul trucks is limited by the fact that the power unit operates predominantly in transient modes, whereas most engineering methods rely on steady-state data. The article proposes an express method in which the per-trip fuel consumption is determined through the equivalent engine operating time at rated power, formed by summing the phases of the transport cycle (loading, loaded travel, dumping, empty return, maneuvering) weighted by the rated-power utilization factors. Unlike lumped tractive calculations that account only for the mechanical work of haulage, the method is based on the energy balance of the diesel engine (the first law of thermodynamics and analysis of the Diesel cycle) and covers the energy expenditure of all trip processes, including non-productive phases and auxiliary systems; the influence of transient modes is captured through calibration of the coefficients against actual operational data. The rated-power utilization factors are justified theoretically from tractive-dynamic relations and compared with the ranges of the national school of mining road transport. The method is verified against the consolidated indicators of the haul-transport balance of the Kalmakyr open pit of Almalyk MMC JSC for 12 months of 2024 for two truck types - BelAZ-75307 (220 t) and BelAZ-75131 (130 t). For the BelAZ-75131 the model parameters were computed independently, without tuning to the reference value, and the calculated consumption matched the actual one (over a sample of 82 thousand loaded trips per year) with a relative error of 1.9 %, which confirms the universality of the coefficient set and is not the result of a single calculation case. The specific fuel consumption is reported in the units traditional for mining, g/(t·km), with the equivalent in l/(t·km). The applicability domain of the express method and its error are substantiated in comparison with simplified (5-10 %) and simulation (2-5 %) methods; the low computational cost of the method allows its embedding into digital systems for operational planning and dispatching of mining road transport.

Keywords

mining haul truck, diesel fuel consumption, engine energy balance, Diesel cycle, rated-power utilization factor, transport cycle, specific fuel consumption, calibration against actual data, express method, surface mining

1. Introduction

Haulage of rock mass is a key technological link of surface mining and the main consumer of energy: loading-and-haulage operations account for up to 50–65 % of the total energy consumption of a mining enterprise [1, 18], while the diesel-fuel costs of mining haul trucks reach 25–40 % of the prime cost of stripping [2]. The accuracy of calculating and rationing fuel consumption therefore has direct economic and environmental significance. The fundamental difficulty of the problem is that the power unit of a mining haul truck operates predominantly in transient (non-steady) modes, in which fuel consumption is, as a rule, higher than the rated value, whereas most calculation methods operate with steady-state data [8]. This largely explains the persistently high error of simplified engineering methods and the continuing interest in their improvement.

The known methods for calculating fuel consumption by mining road transport may be divided into four groups: energy-based (physical), founded on mechanical work and the engine energy balance; empirical-normative (linear and differentiated consumption norms); calculation by transport-cycle elements; and simulation (model-based). A significant contribution to their development was made by studies of the Institute of Mining of the Ural Branch of the RAS: the works of V. L. Yakovlev [2] formulated the principles of rationing diesel-fuel consumption under various mining-technical and economic conditions, while the monographs of V. P. Smirnov and Yu. I. Lel [3] and of P. L. Mariev et al. [4] set out the fundamentals of the theory of heavy-duty open-pit road transport and of tractive calculation. The fundamentals of optimizing the energy costs of mining production were laid in the works of V. S. Khokhryakov [1].

The calculation methods by cycle elements include the method for rationing fuel consumption in deep open pits [7], based on reducing the actual haul-road length to a conventional horizontal haulage distance using an energy criterion — the route-complexity factor μ , which shows how many times the energy costs of motion along the real road exceed those along a horizontal road of the same length. Importantly, the work [8] substantiates the need to account for the operational (transient) load modes of the engine, in which the actual fuel consumption noticeably exceeds the value calculated for steady-state modes.

The fuel-consumption determination methods of A. A. Kuleshov [4, 5] have found wide practical application; a comparative analysis of methods [10] showed that, for the conditions of the Kuzbass open pits, they provide the most accurate results. A separate group is formed by the empirical-normative methods of differentiated norms of fuel and lubricant consumption for heavy-duty haul trucks, historically going back to the industry differentiated norms of 1976 and 1986 and establishing rational principles for introducing correction factors for mining-technical factors; the modern development of this line is represented by the method of reducing mining-technical factors to a single indicator [9] and by the refined method of rationing the full work of the haul truck [6].

Foreign studies of recent years shift the emphasis toward simulation modeling and machine-learning methods. The energy and emission aspects of mining-and-haulage operations are considered in [18]; stochastic optimization of haul-truck dispatching, in [19]; parametric cost models of shovel-and-truck complexes, in [20]. The application of machine learning to predicting the performance and fuel consumption of haul trucks, as well as the influence of road conditions, is developed in [21–23]; a systematization of artificial-intelligence applications in mine planning is given in the review [24]. These works confirm that the most accurate estimates of fuel consumption are provided by simulation modeling, which, however, is computationally expensive and poorly suited to operational engineering calculations.

Despite the considerable body of research, there remains a need for a physically grounded express method that, at low computational cost, would provide engineering accuracy comparable to that of more complex models and be suitable for embedding into digital systems of operational planning and dispatching [12, 15, 17]. The aim of this work is to develop and verify such an express method for calculating the diesel-fuel consumption of a mining haul truck, in which the per-trip consumption is determined through the equivalent engine operating time at rated power on the basis of the diesel-engine energy balance, while the rated-power utilization factors are justified theoretically and calibrated against actual operational data. The object of study is the haul-truck fleet of the Kalmakyr open pit of Almalyk MMC JSC; verification is performed against the consolidated indicators of the enterprise's haul-transport balance for 12 months of 2024 for the BelAZ-75307 and BelAZ-75131 trucks.

2. Research Methodology

The methodological basis of the work consists in systematizing the known approaches to calculating fuel consumption (energy-based physical; empirical-normative; calculation by cycle elements; simulation) and constructing on their basis a physically grounded express method. The energy-based and empirical-normative approaches are reviewed briefly below, after which the proposed method is presented.

Four requirements are imposed on the proposed method: dimensional consistency of the expressions; reliance on the diesel-engine energy balance, covering the energy costs of all processes of the transport cycle and not only the mechanical work of moving the load; accurate account of the actual mode structure of the cycle, including non-productive phases and transient modes (through calibration against actual data); and obtaining the final specific indicator in the units traditional for mining, $\text{g}/(\text{t}\cdot\text{km})$ and $\text{l}/(\text{t}\cdot\text{km})$.

Energy-based method – is the physical basis of all calculation methods. In its lumped form, consumption is related to the mechanical work that the power unit performs to overcome the resistance to motion; such a formulation accounts only for

the work of moving the haul truck and is suitable only for rough estimates, since it does not reflect the engine energy costs of the non-productive phases and transient modes. For each j -th road segment, the total resistance force W_j is determined in a differentiated manner [3, 4]:

$$W_j = G_{cj} \cdot g \cdot (\omega_0 \pm i_j) \quad (1)$$

where: W_j is the total resistance to motion on the j -th road segment, N;

G_{cj} is the gross mass of the haul truck on the j -th segment (for loaded travel $G_c = G + Q_{\phi.py3}$, for empty travel $G_c = G$), t;

ω_0 is the basic specific rolling resistance;

i_j is the longitudinal grade of the j -th segment, %.

The mechanical work on the j -th segment is computed as the product of force and distance travelled. On downhill rolling, where the truck moves under gravity, the engine traction energy is taken equal to zero:

$$A_j = \max(W_j \cdot l_j, 0) \quad (2)$$

where: A_j is the mechanical work performed on the j -th segment, J;

l_j is the length of the j -th segment, m.

The total work over the transport cycle, including additional maneuvering operations:

$$A_{\Sigma} = \sum A_j + A_{ecn} \quad (3)$$

where: A_{Σ} is the total mechanical work per cycle, J;

A_{ecn} is the work spent on maneuvering operations, J.

The volumetric fuel consumption per trip is computed from the energy balance of the power unit:

$$Q_s = \frac{A_{\Sigma}}{\rho_d \cdot Q_c \cdot \eta_e \cdot \eta_{mp}} \quad (4)$$

where: Q_s is the calculated volumetric fuel consumption per trip by the energy-based method, L;

ρ_d is the diesel-fuel density, kg/L;

Q_c is the lower heating value of diesel fuel, kJ/kg;

η_e is the effective efficiency of the engine;

η_{mp} is the efficiency of the haul-truck transmission.

The lumped energy calculation yields only a first approximation and by itself does not provide a deep understanding of the tractive processes: this requires a tractive calculation of the haul truck [4] with allowance for the multiparameter characteristics of the internal-combustion engine, or simulation modeling of the transient modes. Moreover, in the lumped form the mechanical work during loading idling equals zero, whereas fuel is consumed, and the final result (litres per trip) is inconvenient for comparing haul trucks of different payload capacity. These limitations are removed by passing to the energy-balance formulation over cycle elements, set out below.

Empirical-normative method in its most common form operates with reference (normative) specific fuel-consumption indicators referred to the transport work; the same group includes the differentiated norms of fuel and lubricant consumption for heavy-duty haul trucks [6, 9]. The useful transport work A_{mp} is described mathematically as the product of the moved mass and the distance:

$$A_{mp} = Q_{\phi.py3} \cdot l_z \quad (5)$$

where: A_{mp} is the useful transport work per trip, t·km;

$Q_{\phi.py3}$ is the actual mass of the hauled load, t;

l_z is the loaded haulage distance, km.

The volumetric fuel consumption per trip Q_{peuc} is determined through the reference specific-consumption norm:

$$Q_{peuc} = q_{y0.mp} \cdot A_{mp} \quad (6)$$

where: Q_{peuc} is the volumetric fuel consumption per trip, L;

$q_{y0.mp}$ is the normative specific fuel consumption per transport work, l/(t·km).

The actual specific consumption serves as a generalized criterion of energy efficiency:

$$q_{p.mp} = \frac{Q_{peic}}{A_{mp}} \quad (7)$$

where: $q_{p.mp}$ is the calculated specific fuel consumption per unit of transport work, l/(t·km).

The empirical-normative method is simple and yields a clear indicator — consumption per tonne-kilometre — but it is heavily averaged: the normative specific consumption responds weakly to short-term motion modes and changes of grade. To combine the physical rigour of the energy-balance calculation with the clarity of the specific indicator, while also accounting for the engine energy costs of all cycle phases, an integral (energy-specific) express method based on the equivalent engine operating time at rated power is proposed below.

Integral method

The essence of the proposed method consists in reducing all modes of the transport cycle (both travel and idle) to an equivalent engine operating time at rated power, which eliminates averaging errors. The method relies on the energy balance of the diesel engine: by the first law of thermodynamics, the hourly fuel consumption is proportional to the developed effective power through the effective specific consumption q_e , while the effective efficiency $\eta_e = \eta_t \cdot \eta_{mech} \cdot \eta_{aux}$ (thermodynamic efficiency of the Diesel cycle, mechanical efficiency, and efficiency of the cooling and charging systems) for modern open-pit diesel engines of the MTU 16V4000, Cummins QSK60 and Detroit Diesel V12-4000 series equals 0.40–0.45. The current engine load is described by the dimensionless rated-power utilization factor $K(t) \in [0; 1]$, and the per-trip fuel consumption is expressed as the integral of $K(t)$ over the cycle time; thereby the method covers the energy costs of all trip processes — idling, maneuvering, dumping and the operation of auxiliary systems — and not only the mechanical work of moving the load.

For each j -th travel segment, the effective power N_j is determined from the required tractive force and speed:

$$N_j = \frac{W_j \cdot v_j}{3600 \cdot \eta_{mp}} \quad (8)$$

where: N_j is the required effective power on the j -th segment, kW;

W_j is the total resistance to motion on the j -th segment, N;

v_j is the speed of the haul truck on the j -th segment, km/h;

η_{mp} is the efficiency of the haul-truck transmission.

The engine power-utilization factor k_{Nj} in the operating modes is computed as the ratio of the required (current) power to the rated (nameplate) power:

$$k_{Nj} = \min \left(\frac{N_j}{N_o}, 1 \right) \quad (9)$$

where: k_{Nj} is the dimensionless engine power-utilization factor;

N_o is the rated power of the haul-truck engine, kW.

The key parameter — the equivalent engine operating time at rated power over the full cycle $t_{\text{экв}}$ — is formed by summing all phases of machine operation:

$$t_{\text{экв}} = \sum (k_{Nj} \cdot t_j) + k_{N_{xx}} \cdot t_{xx} + k_{N_{man}} \cdot t_{man} + k_{N_{pem}} \cdot t_{pem} \quad (10)$$

where: $t_{\text{экв}}$ is the equivalent engine operating time at rated power, h;

t_j , t_{xx} , t_{man} , t_{pem} are the durations of the travel modes, idling, maneuvering and retarder operation, respectively, h;

$k_{N_{xx}}$, $k_{N_{man}}$, $k_{N_{pem}}$ are the engine power-utilization factors in the corresponding non-productive modes.

The rated hourly volumetric fuel consumption Q_{nom} is determined by the engine constants:

$$Q_{nom} = \frac{q_{y\partial n} \cdot N_o}{1000 \cdot \rho_o} \quad (11)$$

where: Q_{nom} is the rated hourly volumetric fuel consumption, L/h;

$q_{y\partial n}$ is the specific effective fuel consumption at rated power, g/(kW·h);

ρ_o is the diesel-fuel density, kg/L.

The final volumetric fuel consumption per cycle is computed with the introduction of correction factors that adapt the model to actual open-pit conditions:

$$V_{\text{umm}} = Q_{\text{ном}} \cdot t_{\text{экв}} \cdot k_n \cdot k_{\text{клим}} \cdot k_{\text{выс}} \quad (12)$$

where: V_{umm} is the calculated volumetric fuel consumption per cycle by the integral method, L;

$k_n, k_{\text{клим}}, k_{\text{выс}}$ are the factors accounting for the degree of engine wear, the temperature-and-climate conditions and the altitude above sea level.

The calculated specific fuel consumption acquires a strict energy basis:

$$q_{\text{umm}} = \frac{V_{\text{umm}}}{Q_{\text{ф.э.р.з.}} \cdot l_z} \quad (13)$$

where: q_{umm} is the calculated specific fuel consumption by the integral method, l/(t·km).

The developed mathematical model makes it possible to determine fuel consumption with high accuracy at any stage of the trip. However, for operational control and logistics optimization, dispatchers need to assess the actual efficiency of the machines in real time, taking into account the instability of loading. For this purpose, the following calculation module is introduced.

3. Results

The object of study is the haul-truck fleet of the Kalmakyr open pit of Almalyk MMC JSC — one of the largest copper-porphyry open pits of Uzbekistan, with a working depth exceeding 500 m and a mean haul distance of 4.4–4.5 km. Time-study observations of the durations of the transport-cycle operations (loading, loaded and empty travel, dumping, maneuvering) were carried out using data from the enterprise's dispatching system; the motion-mode and calibration parameters are given in Table 2.

The input data are not hypothetical and are taken from the production records of the enterprise. The rolling-resistance factor is taken as $f_r \approx 0.03$ (crushed-stone surface of the open-pit haul roads), the transmission efficiency $\eta_{\text{tr}} \approx 0.85$, the effective specific fuel consumption $g_e = 200\text{--}203$ g/(kW·h), and the rated power $N_e = 1715$ kW (BelAZ-75307) and 1194 kW (BelAZ-75131) — according to the nameplate and operational characteristics of the engines. The rated-power utilization factors K_i are justified theoretically (Table 1) and are consistent with the ranges of the national school of open-pit road transport.

The actual fuel-consumption indicators are taken from the haul-transport balance (HTB) of Almalyk MMC JSC for 12 months of 2024, which contains monthly data on the number of trips, freight turnover, on-duty time, and the normative and actual diesel-fuel consumption. The BelAZ-75307 fleet (29 machines) performed 269.9 thousand trips per year with a freight turnover of 205.87 million t·km; the BelAZ-75131 fleet (31 machines) performed 420.5 thousand trips per year with 173.38 million t·km. The actual annual diesel-fuel consumption was 22.739 and 20.926 million L, respectively, which is 4.8–7.9 % below the normative value; the actual specific consumption is 92.8 g/(t·km) (0.1105 l/t·km) for the BelAZ-75307 and 101.4 g/(t·km) (0.1207 l/t·km) for the BelAZ-75131 (recalculated at $\rho \approx 0.84$ kg/L).

Table 1 Rated-power utilization factors K_i by haul-cycle phase (theoretical justification)

Haul-cycle phase	K_i (Karimov–Tuychiboev)	Theoretical justification	Range of the Kuleshov–Lel–Zyryanov school
Loading	0.10	Idling + drive of hydraulics, compressor and generator	0.10– 0.12
Loaded travel	1.00	Rated power with allowance for rolling resistance ($f_r \approx 0.03$) and grade	0.95– 1.00
Dumping	0.38	Body lift (≈ 9.7 MJ) and maneuvering at the dump	0.38– 0.40
Empty travel	0.60	Ratio $G_{\text{tare}}/G_{\text{gross}}$ with a correction for the downhill mode	0.55– 0.62
Maneuvering	0.12	Intermediate load at low speeds	0.10– 0.12

The parameters α and β of the linear form (18) were calibrated against the reference indicators of the 2024 HTB (Table 2). For the BelAZ-75307, the parameters $\alpha = 23.4$ L and $\beta = 13.9$ L/km were tuned to the reference value of the mean consumption of a productive loaded trip, and the calculated consumption coincided with the actual one — 84.3 L/trip. For the BelAZ-75131, the parameters $\alpha = 16.8$ L and $\beta = 10.6$ L/km were computed independently by formulas (19)–(20), without tuning to the reference value.

The reference value for the BelAZ-75131 was obtained from a sample of productive loaded trips from the 2024 HTB registry (filter: distance $L \in [4.2; 4.8]$ km, cycle time 30–42 min, cargo «stripping», attribute «loaded → dumping»): an annual consumption of 5 280 thousand L over 82 000 trips, which gives $Q_{act} = 64.5$ L/trip. The calculated value $Q_{calc} = 63.3$ L/trip differs from the actual one by 1.9 %. Thus, the verification was performed not on a single case but on a statistically representative annual sample (82 thousand trips, 61 % of all fleet trips), and for the second truck type in an independent-verification mode, which confirms the universality of the set of factors K_i .

Table 2 Calibration and verification of the model against the 2024 haul-transport balance of the Kalmakyr open pit

Parameter	Unit	BelAZ-75307	BelAZ-75131
Payload capacity	t	220	130
Rated engine power N_e	kW	1 715	1 194
Specific effective consumption g_e	g/(kW·h)	200	203
Loading time t_{load}	min	4.0	3.5
Dumping time t_{dump}	min	1.5	1.3
Maneuvering time t_{man}	min	1.6	1.5
Loaded-travel speed ($i=3\%$)	km/h	19.5	37.0
Empty-travel speed ($i=3\%$)	km/h	57.0	55.5
Parameter α (formula 19)	L	23.4	16.8
Parameter β (formula 20, $i=3\%$)	L/km	13.9	10.6
Calculated consumption per trip at $L=4.38$ km	L/trip	84.3	63.3
Actual consumption per trip (HTB 2024)	L/trip	84.3	64.5
Relative error of the model	%	0.0	1.9

The achieved error of 1.9 % was obtained under independent verification on the second truck type and is consistent with the actual annual HTB indicators; it therefore characterizes the method as a whole and not a single fortunate calculation. This is better than the typical accuracy of simplified engineering methods (5–10 % and more) and comparable with the accuracy of simulation modeling (2–5 %, in some cases up to 7 %), which is, however, achieved at the cost of substantially larger computational expense and input-data requirements.

4. Discussion

The obtained results show that a physically grounded express method based on the engine energy balance and the equivalent operating time at rated power provides engineering accuracy sufficient for operational calculations and planning. It is essential that the factors K_i are calibrated against the actual consumption, which already incorporates the influence of the transient engine modes; owing to this, the method indirectly accounts for the consumption raised above the rated value in non-steady modes, without modeling them explicitly.

At the same time, the method does not claim to replace simulation modeling or tractive calculation by the multiparameter engine characteristics [4]: these approaches give a deeper understanding of the transient processes and potentially higher accuracy, but require detailed input data and considerable computational resources. The application domain of the express method comprises operational engineering calculations, rationing, and the comparison of haulage technology options, where speed, transparency and robustness of the result under limited input data are important.

The capabilities of the method are illustrated by parametric dependences. Fig. 1 shows the calculated dependence of the specific fuel consumption on the payload utilization factor of the BelAZ-75307 haul truck (at constant equivalent time). The dependence is hyperbolic in character: when the actual load mass decreases from 220 to 150 t (an incomplete shovel bucket, dilution), the specific consumption rises by almost 45 %, since the useful transport work decreases while the energy is spent on moving the truck tare.

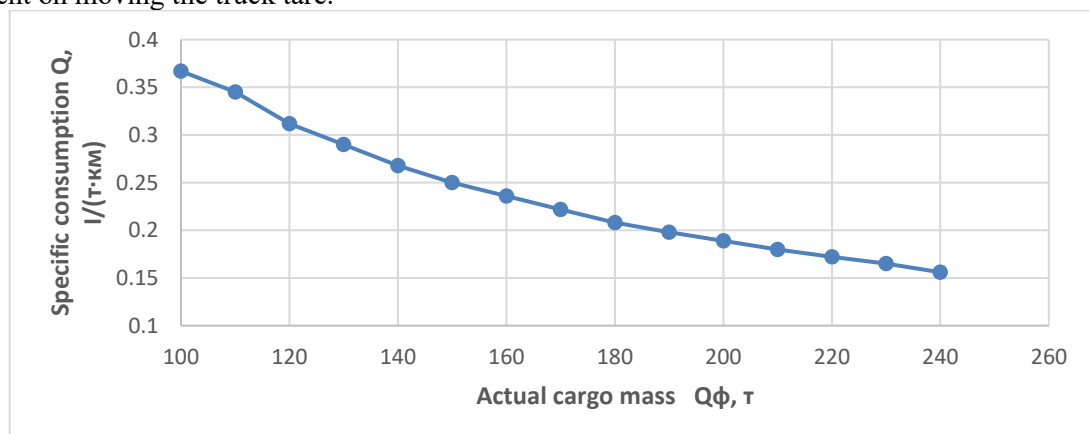


Fig. 1 Calculated dependence of specific fuel consumption on the payload utilization factor of the haul truck

Fig. 2 shows the linear dependence of the absolute per-trip fuel consumption on the idle (non-productive) time. The express method makes it possible to quantify these hidden losses: each hour of idling (for example, while waiting for loading) increases the per-trip consumption by more than 55 litres (at $k_{Nxx} = 0.12$). The classical energy-based method accounts for this factor with large error or ignores it altogether.

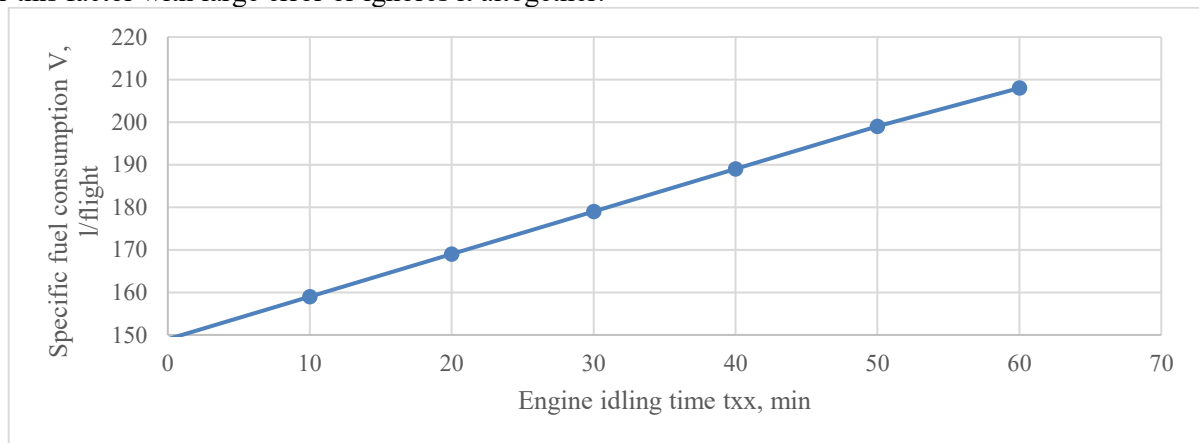


Fig. 2 Linear dependence of per-trip fuel consumption on idle (non-productive) time

Thus, the method not only estimates fuel consumption but also points to the bottlenecks of the transport cycle. Its low computational cost allows it to be embedded into digital dispatching and planning systems (in particular, into the Mining Solver Pro platform [12]) for predictive analytics, operational redistribution of haul trucks, and reduction of idle time.

5. Conclusion

1. A physically grounded integral (energy-specific) express method for calculating the diesel-fuel consumption of mining haul trucks has been proposed, in which the per-trip consumption is expressed through the equivalent engine operating time at rated power on the basis of the diesel-engine energy balance (the first law of thermodynamics, the Diesel cycle); the method covers the energy costs of all phases of the transport cycle, including the non-productive modes.
2. The rated-power utilization factors K_i are justified theoretically from the tractive-dynamic relations and compared with the ranges of the national school of open-pit road transport; their calibration against actual data provides an indirect account of the transient engine modes.
3. The method has been verified against the haul-transport balance of the Kalmakyr open pit for 12 months of 2024 for the BelAZ-75307 and BelAZ-75131 trucks: on a statistically representative annual sample (82 thousand trips), under independent verification of the second truck type, the relative error was 1.9 %. The novelty of the work consists in the closed-form energy-balance formulation of the per-trip consumption with a physically grounded set of factors K_i , calibrated and independently verified against real operational data, suitable for embedding into digital systems of operational planning.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contributions

UF: Conceptualization, methodology development, geomechanical modeling, formal analysis, investigation, and preparation of the original manuscript draft.

KSh: Data collection, field investigations, validation of results, data visualization, manuscript review, and editing.

TE and KV: Literature review, scientific supervision, manuscript editing, and project administration.

All authors have read and approved the final version of the manuscript and agreed to its publication.

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