Mongolian Geoscientist

Original Article

Research on determination of haul truck speed depending on mining and technical conditions

Borya Orkhontuul[1]*, Bayaraa Byambadagva[2, 3], Baldan Purevtogtokh[1]

[1] *Department of Mineral Processing and Engineering, School of Geology and Mining Engineering, Mongolian University of Science and Technology, Ulaanbaatar 14191, Mongolia*
[2] *Ministry of Industry and Mineral Resources, Ulaanbaatar 15160, Mongolia*
[3] *Mongolian Coal Association, Ulaanbaatar 17013, Mongolia*

**Corresponding author: orkhontuulbo@gmail.com, ORCID: 0009-0006-3023-3309*

ARTICLE INFO

Article history:

Received: 24 November, 2024
Revised: 13 October, 2025
Accepted: 18 November, 2025

ABSTRACT

One of the primary methods to enhance the profitability of open-pit mining transportation is to establish and adhere to an operational regime tailored to specific operational and technical conditions. A critical factor defining productivity and safety in these operational regimes is the truck speed. Accurately determining the speed facilitates precise transportation task planning, optimal administrative measures, and operational management capabilities. Several methods exist for determining the speed of dump trucks, with the analytical method commonly used under safety conditions to set speed limits on curvy or steep segments of the road. The graphic-analytical method utilizes dynamics of force and load travel performance to determine the appropriate speed for each road segment. Currently, analytical and graphic-analytical methods used for determining the speed of mining dump trucks are up to 10-15% variance in accuracy, does not fully meet today's requirements. Mining dump trucks operate in stable and variable motion regimes during a single work cycle, and it is impossible to determine the speed during these various regimes using simple analytical methods alone. However, with the advancement of big data processing today, high-precision measurements and production tests can be conducted, enabling the derivation of mathematical equations and models during these motion regimes, which in turn allows for the programming of the entire dump truck travel in a comprehensive model. This study utilized a large dataset from Erdenet open-pit mining operations to define the influence of operational and technical factors such as mine depth, distance, road gradient, and pavement type on the speed of movement. This methodology enables conducting various analytical tests, developing models, and quickly determining the speed of movement under specific production conditions.

Keywords: roadways, transportation routes, direction, speed of dump trucks

INTRODUCTION

The speed of dump trucks is determined through analytical, graphic-analytical, and empirical modeling methods. The analytical method is primarily used under safe operating conditions to set speed limits that prevent skidding in curvy road sections. This includes setting safe speed limits based on the road curvature radius, cross slope, and load conditions, and establishing speed limits on steep descents to ensure safe operation.

The graphic-analytical method is used on road sections that are curvy and steep to determine the average speed of a dump truck by utilizing the dynamics of force (Kuznetsov and Kosolapov, 2022) and travel performance. This method can determine truck speeds with an error margin of 15-30%.

The most accurate method to determine dump truck speed is through experimental modeling. The simplest form of this testing involves chronometry or direct measurement under production conditions. Modeling considers various operational and mining condition parameters, including the technological implemented of the mine and frequent changes in the road's gradient and curvature over short distances, causing significant variations in movement speed within a very short time (Orkhontuul, 2007; Purevtogtokh, 2019).

Speed limits are set throughout all sections of the road according to safety regulations and standards specified for the mine. As the road gradient increases, the speed of the vehicles decreases, which leads to higher fuel consumption (Terekhin, 2001; Purewtogtokh et al., 2020) and increased tire wear (Baafi, 1993), and deteriorates the safety conditions of the movement. Conversely, when the slope decreases, the scale of mining operations increases, and the length of the road extends. Therefore, adjusting the speed of the dump trucks to match the mining road conditions is highly important aspect of mining operations (Orkhontuul, 2006).

STUDY AREA

Haulage and Transportation Department (HTD) of the Erdenet mine was initially established in 1978 under the name "General Administration Office," and later reorganized into the "Mine Haulage" unit by the director's order on June 14, 1978. Subsequently, on September 20, 1978, the unit began operating BelAZ haul trucks at the newly commissioned "Transportation Fleet or Maintenance Shop" (Maintenance Shop No. 1), to aim of ensuring a high levels of equipment readiness. From 1978 to 1988, hauling of waste material and low grade ore to waste dumps and the haulage of copper-molybdenum ore to the Processing Plant were performed using 40-ton capacity BelAZ-548A dump trucks. Starting in 1988, 110-ton capacity BelAZ-7519 trucks were introduced, and from 1994 onwards, 120-ton capacity BelAZ-75122 trucks were used. In 1996, Japanese Komatsu firm's 78-ton capacity HD-785 and US made Caterpillar firm's 136-ton capacity CAT-785B dump trucks were employed, significantly upgrading the technological and processing capabilities of the mining operations (Erdenet mine began operating at project nameplate capacity in the early 1980s), and its capacity has increased along with the volume of ore processed, correspondingly increasing the number and capacity of hauling units (Orkhontuul et al., 2023).

The haulage vehicle fleet began to get modernized in 1989 with higher capacity dump trucks, by decommissioning older models like BelAZ-548 and BelAZ-7523 based on their conditions. Between 1989 and 1995, 46-90% of the haulage tasks were performed by 28-41 units of BelAZ-548 and BelAZ-7523. From 1996 to 1997, 1.9-12% of the tasks were carried out by 5-12 units of the same models. From 1997 to 2003, the average number of dump trucks fluctuated between 20-25, incorporating newer

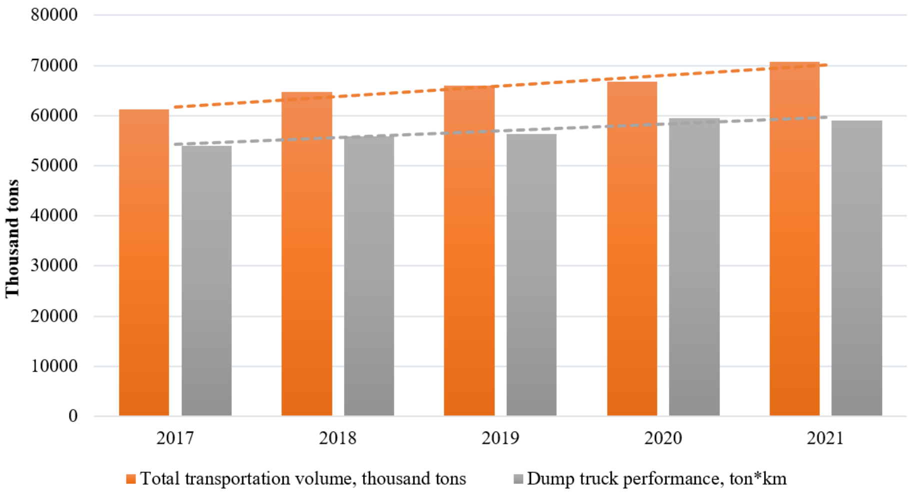

Fig. 1. Hauled tons and dump truck performance (2017-2021)

models such as BelAZ-75145, BelAZ-75131, CAT-785B, and HD-785 into the fleet. Since 2010, the fleet has employed BelAZ-75131 trucks with KTA 50 engines, which have a 130-ton capacity and are extensively used in mining operations in countries like Egypt, Turkey, Iraq, China, Bulgaria, Iran, and Mongolia (Purevtogtokh et al., 2020).

From 2017 to 2021, the last five years under review, the key performance indicators in transportation have shown an annual increase of 1.2-5.9% in ore transportation volumes (Fig. 1). The growth trend in hauled tons increase averaged 3.7% annually, with a 1.2% increase in 2020 compared to the previous year. As for the dump truck's productivity, there was an average annual increase of 2.3%, with a 0.7% decrease in 2021 compared to the previous year.

MATERIALS AND METHODS

Open-pit mining roads

Open-pit mining roads are classified as utility and production roads, which are further divided by their duration of use into permanent and temporary, and by their location into bench access, ramps, surface, and dump access roads (Purevtogtokh, 1992). Permanent roads include the main routes used to transport minerals to storage, processing plants, and transfer points. These roads are used throughout the entire operational period of the mine or for a specified duration, with an average vehicle speed of 40-50 km/h. Additionally, roads within the mine that are used for 5-10 years for soil removal and reach up to the dumps are classified under permanent roads, with speeds on these roads up to 40 km/h. Temporary roads, which are used for up to 2 years on bench access and dumps, support truck speeds ranging from a minimum of 10-15 km/h to a maximum of 20 km/h (Purevtogtokh et al., 2014). The mining roads are classified into three levels based on the load they handle. The components of the mining road system and their dimensions are shown in Table 1, which also presents the calculation speeds at intersections and junctions, where speeds are generally reduced by half, but must not be less than 5 km/h (Purevtogtokh, 2019).

The economic and technical performance of mining transportation is significantly influenced by the road gradient. As the gradient increases, the speed of movement decreases, leading to higher fuel consumption and tire wear, and worsening safety conditions. The road gradient is expressed using the following formulas (Purevtogtokh, 2019) and Fig. 2:

By permille (‰)

$$1‰ = 1000\ \mathrm{tg}\alpha \approx 1000\ \sin\alpha \qquad (1)$$

In percentage (%)

$$1\% = 100\ \mathrm{tg}\alpha \approx 100\ \sin\alpha \qquad (2)$$

In other words, 1000 tgα = 0.1 % = 1‰ and the

Table 1. Approved Speeds for dump trucks, km/h

Road type and description	Expected usage duration	Average movement speed limit, km/h	Road classification
	Permanent roads		
Main hauling roads connecting to tipping points, processing plant and stockpiles	Life of mine	50-60	I
Mine access and waste dump connection roads	Life of mine, as pit reaching lower elevations and pushbacks	20-25	I
Roads connecting with from main roads to waste dump	Life of mine (typically 8-10 years)	30-40	I
Waste dump access road	Life of mine	15-20	II
Roads connecting different sections of the waste dump	Usage duration of certain sections (typically 3-5 years)	20-25	II
	Temporary roads		
In pit roads accessing different levels, phases and benches	Dependant on level/ phase/ bench duration (typically 1-2 years)	10-15	III
Waste dump roads	In line with waste duration period	10-15	III

nomogram for converting gradient expressed in degrees, percent, and permille" is shown in Fig. 1. The maximum gradient of the road is selected based on the characteristics of the dump truck chosen for specific mining conditions. Initially, during the project planning phase, one can select using Table 1. However, for roads of Class II and III, it is possible to increase the gradient up to 10‰, and for roads used up to one year, up to 30‰ is allowable (Thompson and Visser, 2006; Adair et al., 2015).

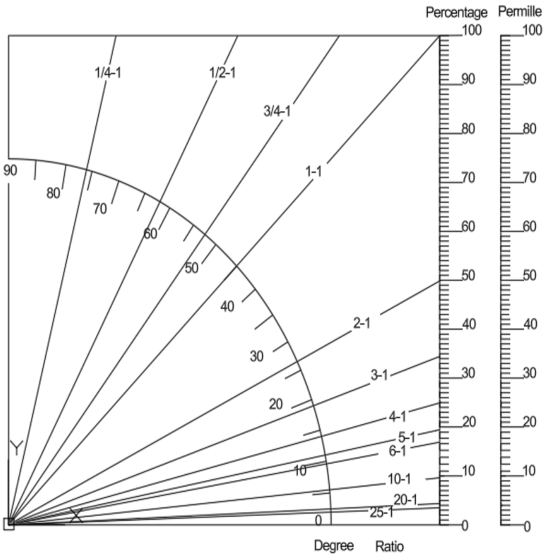

Fig. 2. Nomogram for converting gradient expressed in degrees, percent, and permille

Basic equation of vehicle motion

The driving power of a vehicle depends on the engine capacity, type of power transmission, the friction between the road and the tires, and the total mass of the vehicle. The driving force is categorized into internal, tractive, and excess (Kozyaruk and Kuleshov, 2003):

- Internal driving force represents the total power generated by the engine's operation without considering any transmission losses
- Tractive driving force is generated by the interaction between the road and the tires, propelling the vehicle forward (Fig. 3).
- Excess Driving Force is defined by the difference between the driving force and the opposing forces of motion.
  - P_3 -Driving weight or load acting on the rotating wheel,
  - M -Rotational moment,
  - F-F=M -Force equal to the opposing moment.

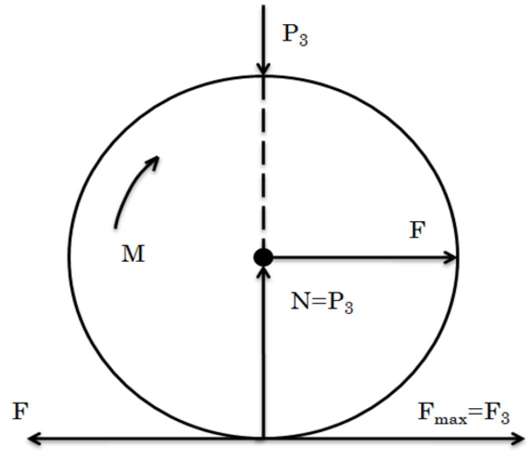

Fig. 3. Schematic of force in a rotating wheel

The maximum driving force that a vehicle can generate is (Alexandrov et al., 2019):

$$F_3 \leq \frac{3600 \cdot N_e}{v} \cdot \eta_x \cdot \eta_{am} \cdot \eta_g, H \qquad (3)$$

where: N_e – Actual engine power, kW;

η_x -Efficiency coefficient of the power transmission mechanism, with hydro-mechanical transmission

η_x=0.7...0.72, with electro-mechanical transmission η_x=0.69...0.71

η_{am}=0,85…0.88 -Coefficient accounting for energy losses in auxiliary mechanisms,

η_g -Efficiency coefficient of the rotating wheel -0.9,

υ -Speed of the vehicle, km/h.

Maximum Driving Force Expression is constrained by friction rolling resistance.

$$F_{max} \leq 1000\, P_d \cdot \psi;\ H \qquad (4)$$

where: $P_d=k_d \cdot P$ -the driving weight or load acting on the driving wheel, kN;

P -total weight of the vehicle, in kN;

k_d -coefficient representing the load on the driving wheel

ψ -coefficient of friction;

Total Resistance Force of the Vehicle /W/ :

$$W = W_p + W_g + W_c + W_w + W_i \qquad (5)$$

W_p represents the primary resistance force due to the interaction between the wheel and road, including the deformation of the wheel and road surfaces, and is calculated as:

$$W_p = \omega_a \cdot P \qquad (6)$$

where: ω_a – is the vehicle's specific primary resistance coefficient (N/kN)

W_g is the resistance force due to the gradient of the road, equivalent to the vehicle's weight times the road gradient

$$W_g = i \cdot P\ ;\ H \qquad (7)$$

where: i – road gradient, ‰

Resistance force due to road curvature, calculated when the radius of curvature is less than or equal to 200 meters

$$W_c = \omega_R \cdot P = \Delta i \cdot P\ ;\ \mathrm{H} \qquad (8)$$

where: w_R=Δi=30·(200-R)/200 -a coefficient dependent on curvature, N/kN

Δi -equivalent gradient of coefficient dependent on curvature, ‰

R -the radius of curvature, m

Aerodynamic resistance force of the vehicle:

$$W_w = \lambda_w \cdot F(\upsilon \pm \upsilon_w)^2 \qquad (9)$$

where: λ_w=0.55…0.7 -the aerodynamic resistance coefficient

F -the frontal area of the vehicle, m², υ -speed of the vehicle , km/h; υ_w -wind speed, km/h

Inertial resistance force of the vehicle:

$$W_i = 1000 \cdot \frac{P}{g} \cdot (1+\gamma) \cdot \left(\frac{dv}{dt}\right) = j \cdot P \qquad (10)$$

where: *g* -acceleration due to gravity (kg·m/s²),

dv/dt = a -vehicle acceleration (m/s²)

γ -coefficient accounting for the inertia of rotating parts. This coefficient depends on the type of power transmission system, varying with the load direction from 0.03 to 0.01 for hydro-mechanical transmissions when loaded, from 0.085 to 0.07 when unloaded, and from 0.1 to 0.15 for electric-mechanical transmissions.

$$j = \frac{1000 \cdot (1+\gamma)}{g} \cdot \frac{dv}{dt} \qquad (11)$$

j -coefficient of inertial resistance

The vehicle's basic motion equation is central to solving specific issues related to hauling equipment utilization, driving mode, and their organization (Purevtogtokh, 2019).

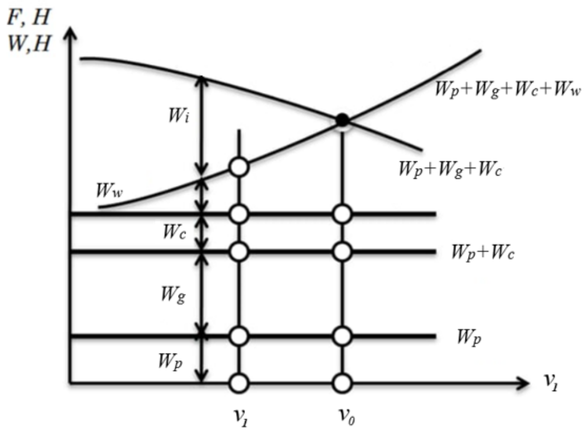

Fig. 4. Diagram of the relationship between vehicle speed, force, and driving mode

From the driving force diagram in Fig. 4 and Table 2, the condition for an equipment to continue moving without reducing speed under modes I and II is expressed by the formula (Kuleshov et al., 2003; Lan and Menendez 2003)

$$F_3 \geq W = W_p + W_g + W_c + W_w + W_i \qquad (12)$$

If the aerodynamic resistance force acting independently of the vehicle's weight is adjusted to the left side of the equation, the basic equation of vehicle motion emerges

$$\frac{F_3 - W_c}{P} = w_a \pm i + w_R + j \qquad (13)$$

The left side of the equation or the force per unit weight exerted dynamically is defined as D

$$D = \frac{F_3 - W_w}{P} \qquad (14)$$

Table 2. Vehicle driving modes

Parameters	Driving modes		
	I	II	III
Force Ratio	F>W	F=W	F<W
Inertial Resistance	+	0	-
Acceleration	+	0	-
Driving Mode	Accelerating	Constant	Slowing down

On straight road sections with steady movement (W_R= 0):

$$D = \omega_a \pm I \quad (15)$$

When operating in a driving mode on a steep road:

$$D = \omega_a - i + j \quad (16)$$

When moving by its own inertia on a steep road

$$\frac{W_w}{P} = \omega_a - i + j \quad (17)$$

In braking mode:

$$\frac{-B-W_w}{P} = w_a - i + j \quad (18)$$

where braking force is:

$$B \leq 1000 \cdot P_T \cdot \psi_T \quad (19)$$

where: B -Braking force, N,

P_T -Braking weight or load on the braking wheel, N,

Under normal conditions, or when all wheels are braking, P_T = P

Ψ_T -Coefficient of friction during braking

Methods determining speed of dump trucks

Methods for determining the speed of a dump truck are primarily discussed in previous section and typically use the analytical method for challenging road conditions. For instance, in mines with steep inclines, the allowable speed limit under braking conditions ensures safe operation, while on curvy road sections, the safe speed limit to avoid skidding is defined by the following formula (Bester, 2000).

$$3.6 \cdot \sqrt{R \cdot (\psi_x \pm i_x)} \geq v_R, \text{km/h} \quad (20)$$

where: R -the radius of the road curve, in meters

ψ_x -the coefficient of lateral friction (ranging from 0.3 to 0.45);

i_x -lateral slope of the road (ranging from 0.02 to 0.06).

The average speed for loaded and unloaded directions on each segment of the road under specified conditions is calculated using the following formula:

$$v_g = \frac{\sum_{j=1}^{n} v_j \cdot l_j}{\sum l_i}; \quad (21)$$

where: v_j, l_j -the designated average speed for segment j of the road, loaded (unloaded) in km/h;

l_j -the length of segment j of the road, in kilometers.

RESULTS

The average speed of movement for both loaded and empty dump trucks at the Erdenet open-pit mine was analyzed using data from January 2021 to July 2023. Consideration was given to the hauling routes from the mining face to the tipping points. In July 2021, transportation occurred over 22 routes, while in December 2021, 15 routes were used. In July 2022, the number of routes decreased to 11, and by December 2022, only 10 routes were being utilized (Byambadagva, 2022).

Calculations using the Micromine software for the gradients, elevations, and turning radius of each segment of the transportation routes showed the following:

- The bench access routes varied from 11 to 101.6 m in length.
- The gradient segments ranging from 146.5 to 989.7 m in length and gradients between 73.7-87.7‰ (or 4.6-5.7%).
- Surface off the pit roads ranged from 54.5 to 88.6 m in length, while waste dump roads had sections between 19.9 to 104.6 m in length. These road segments had turning radius ranging from 51 to 105 m.

The average speeds for loaded and empty directions of dump trucks at the Erdenet open-pit mine were analyzed from January 2021 to July 2023. The transportation routes from the mining face to the tipping points are considered (Orkhontuul et al., 2024a).

Loaded Direction:

- July: The highest average speed recorded was 22 km/h from elevation level 1265, while the lowest was 20.01 km/h from elevation level 1250 towards the processing plant (Fig. 5a).
- December: The highest average speed was 22.4 km/h from elevation level 1235, and the lowest was 20.6 km/h from elevation level 1265 towards the processing plant (Fig. 5b).

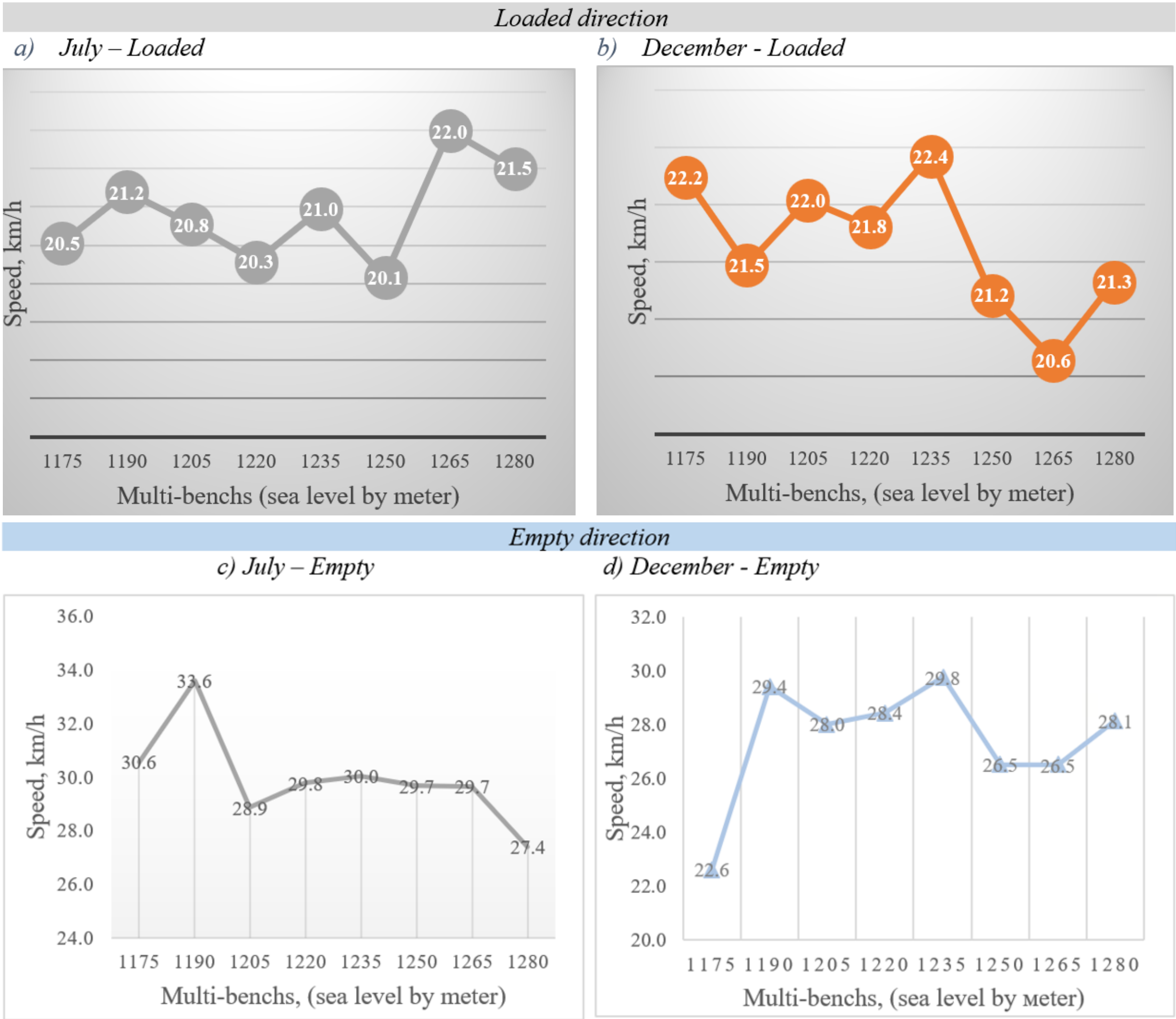

Fig. 5. The average speed for the Processing plant route (2021-2023)

Empty Direction:

- July: The highest speed was 33.6 km/h at the descent part from elevation level 1190, and the lowest was 27.4 km/h towards the descent from elevation level 1280 (Fig. 5c).
- December: Over the last three years, the highest average speed in December was 29.8 km/h at the mining route of elevation level 1235, and the lowest was 22.6 km/h at elevation level 1175 (Fig. 5d).

The comparison of the average speeds in July and December for the processing plant shows that the speeds in the empty direction were 40% higher than those in the loaded direction. This indicates the need to differentiate the speeds in loaded and empty directions based on safety conditions and the technical capabilities of the hauling.

Determination of dump truck speeds based on mining and technical factors

In production conditions, each dump truck in the fleet is registered in the Pitram system with specific parameters such as loading and tipping locations, speed movement and road characteristics, actual capacities, and the duration of a full cycle. These parameters are divided into loaded and empty directions and analyzed from January 1, 2021, to October 1, 2023, resulting in a total of 116.42 million data points. During the study, it became necessary to process the data in the Pitram system due to the selection of particular routes for the consolidated diagram. Throughout the data processing phase, there were several instances where the monthly data for some dump trucks were entirely omitted. If we consider the proportion of total data over different time periods, both

Table 3. Regression of truck speed in loaded direction in filtered data

Filtered data	Regression	Equation
Filtered data by 10%- linear	$u_{load}=20.03+1.11 \cdot L-0.008 \cdot W$	(22)
Filtered data by 15%- linear	$u_{load}=21.9+1.09 \cdot L-0.03 \cdot W$	(23)
Filtered data by 20%- linear	$u_{load}=21.89+1.02 \cdot L-0.03 \cdot W$	(24)
Filtered data by 10%- quadratic	$\boldsymbol{u_{load}=22.8-0.17 \cdot L^2-0.00006 \cdot W^2+0.001 \cdot W \cdot L+2.43 \cdot L-0.04 \cdot W}$	(25)
Filtered data by 15%- quadratic	$u_{load}=23.88-0.65 \cdot L-0.01 \cdot W-0.00001 \cdot W^2+0.18 \cdot L^2-0.0006 \cdot W \cdot L$	(26)
Filtered data by 20%- quadratic	$u_{load}=22.57-0.38 \cdot L-0.008 \cdot W-0.00005 \cdot W^2+0.14 \cdot L^2-0.0001 \cdot W \cdot L$	(27)
W -the total resistance to movement, kN; L -the length of route, km		

Table 4. Regression of truck speed in empty direction in filtered data

Filtered data	Regression	Equation
Filtered data by 10%- linear	$v_{empty}= 22.36 + 1.74 \cdot L - 0.01 \cdot W$	(28)
Filtered data by 15%- linear	$v_{empty}= 22.33 + 1.64 \cdot L - 0.01 \cdot W$	(29)
Filtered data by 20%- linear	$v_{empty}= 24.71 + 1.5 \cdot L - 0.01 \cdot W$	(30)
Filtered data by 10%- quadratic	$\boldsymbol{v_{empty}= 20.7 - 0.17 \cdot L^2 + 0.00001 \cdot W^2 - 0.001 \cdot W \cdot L +3.47 \cdot L -0.001 \cdot W}$	(31)
Filtered data by 15%- quadratic	$v_{empty}= 17.72 + 4.19 \cdot L + 0.0008 \cdot W - 0.00006 \cdot W^2-0.27 \cdot L^2 -0.001 \cdot W \cdot L$	(32)
Filtered data by 20%- quadratic	$v_{empty}= 20.77 + 3.43 \cdot L - 0.03 \cdot W - 0.00003 \cdot W^2 - 0.22 \cdot L^2 +0.005 \cdot W \cdot L$	(33)
W -the total resistance to movement, kN; L -the length of route, km		

July and December of 2021 accounted for 25% of the data, while both July and December of 2022 each accounted for 20%, and July 2023 data made up 10%. Over time, the proportion of data has been decreasing, which could be attributed to improvements in the system and possibly due to the aging and obsolescence of the technological transport vehicles.

To understand how operational and technical factors influence the speed of dump trucks, data was refined and analyzed through regression models using the Python programming language, based on real-time operational data from 2021 to 2023. The speed impact of transportation distances (L), total movement resistance (W) was analyzed with linear and quadratic models, shown in Tables 3 and 4. The quadratic regression models generally showed higher performance than linear models.

DISCUSSION

From the Table 3 and 4, it is evident that the quadratic regression models show higher significance in their test statistics compared to the linear models. The Fisher's F-test values for the quadratic models are FT=10278.2, FT=3021.9, FT=2988.0, all significantly exceeding the table value $F_x=3.26$. This confirms that the factors' influences are statistically significant at the corresponding confidence levels. The high significance and impact levels of the 10% density quadratic dependencies were used to find the regression models for both loaded and empty directions of dump truck speed times.

To better understand the influence of operational and technical factors in Fig. 6, the second-order dependencies, which show higher confidence indicators, were expressed through the regression mathematical models for the

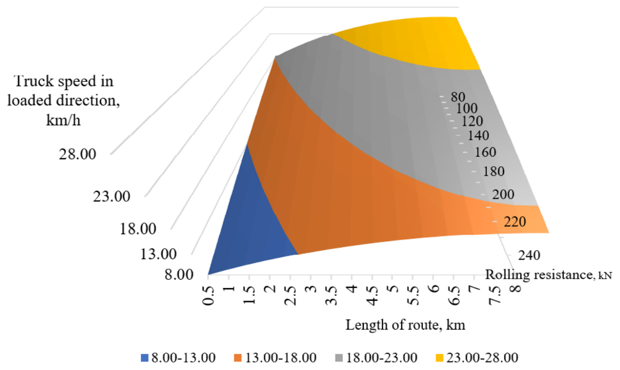

Fig. 6. Correlation between factors affecting the speed of loaded direction

duration of hauling movement on the hauling units (loaded) as:

$$\upsilon_{load} = [22.8 - 0.17L^2 - 6.3 \cdot 10^{-5}[P_{aj}(\omega_{aj} + i_{aj}) + P_{xj}(\omega_{xj} + i_{xj})]^2 + 0.0010[P_{aj}(\omega_{aj} + i_{aj}) + P_{xj}(\omega_{xj} + i_{xj})]L + 2.43L - -0.04[P_{aj}(\omega_{aj} + i_{aj}) + P_{xj}(\omega_{xj} + i_{xj})], \quad km/h \qquad (34)$$

where: i_{aj} , i_{xj} -average gradient for the route during loaded and empty periods,‰;

ω_{aj}, ω_{xj} -resistance coefficient during loaded and empty movement, H/кH;

P_{aj} , P_{xj} -weight of the vehicle during loaded and empty travel, кH;

L -hauling distance, km.

For the empty direction in Fig. 7, the regression model for movement duration is expressed as:

$$\upsilon_{empty} = [20.7 - 0.17L^2 - 1.1 \cdot 10^{-5}[P_{aj}(\omega_{aj} + i_{aj}) + P_{xj}(\omega_{xj} + i_{xj})]^2 - 0.001[P_{aj}(\omega_{aj} + i_{aj}) + P_{xj}(\omega_{xj} + i_{xj})]L + 3.47L - -0.001[P_{aj}(\omega_{aj} + i_{aj}) + P_{xj}(\omega_{xj} + i_{xj})]], \quad km/h \qquad (35)$$

The process to determine the speed of technological transport vehicles in both loaded and empty directions based on operational and mining conditions involves the following key steps in machine learning: modeling, determining dependencies, formulating, and testing. This process is executed using the Python programming language in the Jupiter notebook environment, where regression models are evaluated using two methods (Orkhontuul et al., 2024b):

1. Sample Evaluation Method: Initially used, this method demonstrates how well the model fits actual measurement values. Measurements are randomly divided into training and testing segments using the scikit-learn library's train_test_split function:

x_train1, x_test1, y_train1, y_test1 = train_test_split(x_data, y_data, test_size = 0.1, random_state = 0)

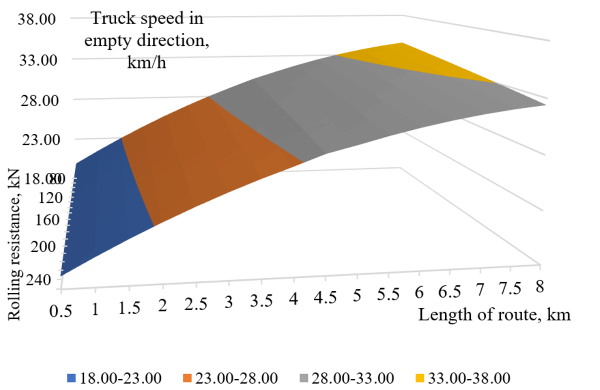

Fig. 7. Correlation between factors affecting the speed of empty direction

For loaded/empty direction:

- x_data Independent variable measurements df['lload'] / df['le']
- y_data: Dependent variable measurements df['vl'] / df['ve']
- x_train, y_train: Training segment of the measurements
- x_test, y_test: Testing segment of the measurements
- size: Proportion of the data for testing (10%)
- random_state: Randomly splits the measurements into training (90%) and testing (10%) subsets.

In the loaded direction, the coefficient of determination during the training segment was 0.537 in Fig. 8a, and in the testing segment, it was 0.442 in Fig. 8b. In a controlled data portion (40%), it was 0.548. In the empty direction, the coefficient of determination in the training segment was 0.88, and in the testing segment, it was 0.876. In a controlled data portion (40%), it was 0.876.

2. Another method to evaluate the model is by using the cross_val_predict() function to estimate the output values. For the loaded direction, the cross_val_predict() function is used to predict output values:

yhat = cross_val_predict(lre, x_data[['lload']], y_data, cv = 4)

cross_val_predict () The output of cross_val_predict() for 'lload' returns values such as array in Fig. 8a ([25.35915064, 25.45380986, 25.43196611, 25.49219629, 25.36707034]).

For the empty direction, to find the predicted values in Fig. 9a:
yhat = cross_val_predict(lre, x_data[['le']], y_data, cv = 4)
cross_val_predict () The output of cross_val_predict() for 'le' returns values such as array [27.4012591 , 27.27453097, 27.37591347, 27.35056785, 27.33789503].

Results from these two methods are shown in Fig. 8, and the regression model for the speed indicators in the loaded direction has been compared with actual values using Python programming to calculate effectiveness.
From Fig. 8, which compares the model's calculated and actual speed values for the loaded direction, the model was executed at a 95% confidence level. The regression model shows a deviation of -6.1% at minimum and 15.5% at maximum, with an average error of 13.69%, indicating that the regression model sufficiently represents the actual values.
From Fig. 9b, which evaluates the model for the empty direction, it is observed that with a 95% confidence level, the regression model shows a deviation of -8.8% at minimum and 5.5% at maximum, with an average error of 0.71%. This demonstrates that the regression model fully represents the actual values for the empty direction.

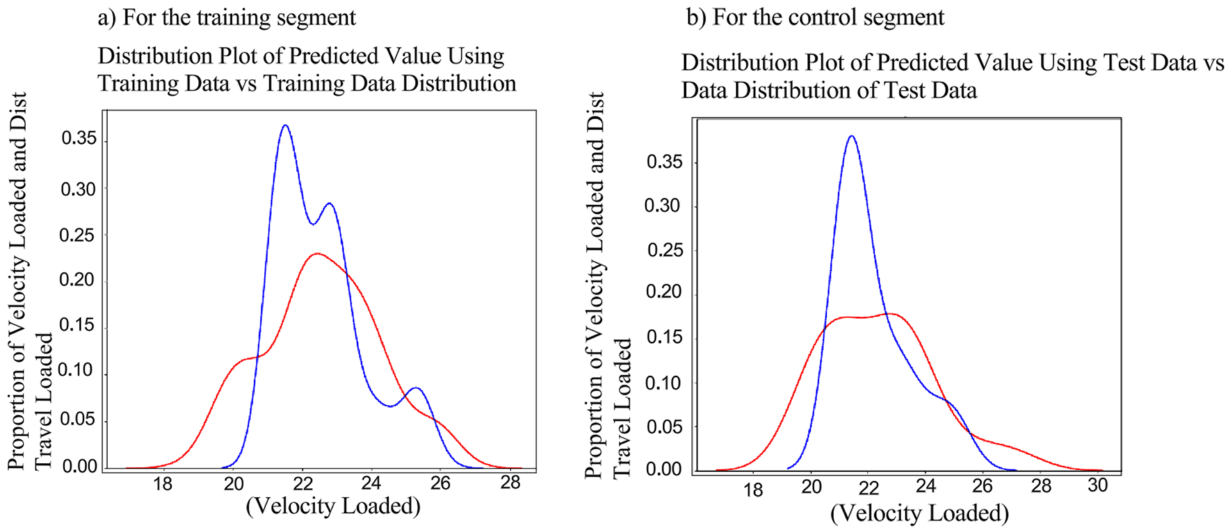

Fig. 8. Comparison of the calculated and actual speed values using the regression model for the Loaded direction through the training and control segments

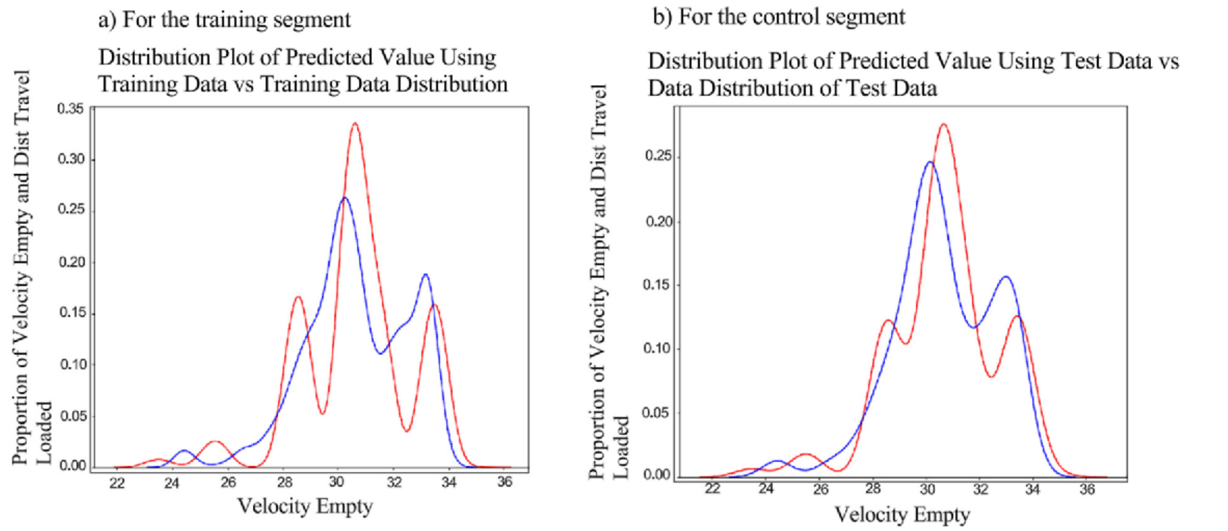

Fig. 9. Comparison of the calculated and actual speed values using the regression model for the Empty direction through the training and control segments

CONCLUSION

In this study, a big dataset of 116.42 million data points was compiled, encompassing real-time data from January 1, 2021, to October 2023. This data includes each dump truck's loading and empty locations, travel time, actual load, and the duration of a full cycle, as recorded in the Pitram system. Data was categorized by loaded and empty directions and was further supplemented by road attributes, including mine layouts and surveyor measurements of the mine's working conditions.

Using this extensive dataset, relationships were identified between factors such as mine depth, transportation distance, road gradient, road surface type, and the actual load of the dump trucks. These relationships were expressed through regression equations. The equations enable analytical testing, model development, and the rapid determination of speed and productivity under specific operational conditions. A differential speed model for the technological transport vehicles of the Erdenet Mining Corporation was developed based on mine depth and transportation distance and was expressed in tabular form.

With these regression equations, a model was developed to determine speed and productivity across various routes in open-pit mine hauling routes, depending on factor variations. Using Python, a numerical simulation experiment was conducted with this model to define differential norms of dump truck productivity per shift. This differential norm can be applied in production planning, management, organization, and control stages.

ACKNOWLEDGEMENTS

Authors would like to thank Autotransportation agent of the Erdenet Mining Corporation for the collaboration and support of this project.

REFERENCES

Adair, L., Soofastaei, A., Aminossadati, S.M., Kizil M.S., Knights, P. 2015. Rolling Resistance in Haul Truck Operations. Australian Mining, vol. 1(1), p. 85-88.

Alexandrov, V.I., Vasilyeva, M.A., Koptev, V.Y. 2019. Effective Power and Speed of Mining Dump Trucks in Fuel Economy Mode. Journal of Mining Institute, vol. 239, p. 556-563. https://doi.org/10.31897/pmi.2019.5.556

Baafi, E.Y. 1993. Tyres and wheels. Methods of measuring rolling resistance. British Standards Institute: London. p. 14-16.

Bester, C.J. 2000. Truck speed profiles. Transportation Research Record, vol. 1701(1), p. 111-115. https://doi.org/10.3141/1701-14

Byambadagva, B. 2022. Energy consumption analysis of open pit mining transportation systems. PhD thesis, Mongolian University of Science and Technology, Ulaanbaatar, 144 p. (in Mongolian)

Kozyaruk A.E., Kuleshov A.A. 2003. Main directions of improvement of traction drive of quarry automatic dump trucks. Gornyi zhurnal, vol. 2003(3), p. 54-60. (in Russian). https://www.rudmet.ru/journal/1079/article/17651/

Kuznetsov, D., Kosolapov, A. 2022. Dynamic of performance of open-pit dump trucks in ore mining in severe climatic environment. Transportation Research Procedia, vol. 63, p. 1042-1048. https://doi.org/10.1016/j.trpro.2022.06.104

Lan, C.J, Menendez, M. 2003. Truck Speed Profile Models for Critical Length of Grade. Journal of Transportation Engineering, vol. 129(4), p. 408-419. https://doi.org/10.1061/(ASCE)0733-947X(2003)129:4(408)

Orkhontuul, B. 2006. Definition methods of parameters of truck exploitation in open pit mining. PhD thesis, Mongolian University of Science and Technology, Ulaanbaatar, 148 p. (in Mongolian)

Orkhontuul, B. 2007. Analysis of truck dismounting process. 2007 International Forum on Strategic Technology, Ulaanbaatar, Mongolia, IEEE, p. 457-458. https://doi.org/10.1109/IFOST.2007.4798630

Orkhontuul, B., Purevtogtokh, B., Sugarragchaa, Ch., Battsetseg, Ts., Delgermurun, D. 2023. Dynamic normalization of technological dump truck applications. Erdenet Mining Corporation funded research project, Ulaanbaatar, Mongolia, 184 p.

Orkhontuul, B., Byambadagva, B., Purevtogtokh, B., Uyansanaa, U., Badamgarav, D. 2024a. Determination of fuel consumption of dump trucks depending on mining and technical

conditions. Proceedings of the 2024 Resource Operators Conference (ROC2024), University of Wollongong, Australia, p. 341-349.
https://hdl.handle.net/10779/uow.27684852.v1

Orkhontuul, B., Battsetseg, Ts., Serchmaa, Ts., Oyunkhuu, U., Zulaa, N., Batsanaa, U. 2024b. Open-Pit mining auto transport data processing. Proceedings of the 2024 Resource Operators Conference (ROC2024), University of Wollongong, Australia, p. 360-367.
https://hdl.handle.net/10779/uow.27684852.v1

Purevtogtokh, B. 1992. On the issue of mathematical modeling of the movement of mining dump trucks. Unpublished PhD thesis, Leningrad Mining Institute, Russia. (in Russian)

Purevtogtokh, B., Orkhontuul, B., Enkhchuluun, B. 2014. Possibility of introducing cyclical-flow technology at the JV "Erdenet" Mining. Science and Innovation to the North, Proceeding Mirnye 2014, p 5-7. (in Russian)

Purewtogtokh, B., Byambadagwa, B., Enkhchuluun, B. 2020. The determination of the fuel consumption of mining dump trucks. Mining Informational and Analytical Bulletin, vol. 3(1), p. 557-567. (in Russian)
https://doi.org/10.25018/0236-1493-2020-31-0-557-567

Purevtogtokh, B. 2019. Scientific basis of optimal selection and exploitation of open pit mine auto transport means. ScD thesis, Mongolian Academy of Sciences, Ulaanbaatar. (in Mongolian)

Thompson, R.J., Visser, A.T. 2006. The impact of Rolling Resistance on Fuel, Speed and Costs. 2006, University of Pretoria, South Africa.

Terekhin, E.Yu. 2001. Study on the Energy Efficiency of Deep Mining transport systems. Unpublished PhD thesis, Ekaterinburg, 204 p. (in Russian)