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LOW-CARBON TRANSITION PATHWAYS IN THE TRANSPORTATION OF MINING RAW MATERIALS

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Abstract. The article explores the pressing issue of global warming—reducing greenhouse gas emissions during the transportation of mineral raw materials from the deposit to the processing plant. To optimize the raw material transportation route, it is advisable to use combined transport, integrating different types of transportation. Each type of transport is rationally utilized on a specific section of the route depending on its technical and technological parameters. Road transport is most suitable for the specific working conditions within the boundaries of the quarry field. When the processing plant is located at a significant distance from the quarry, railway transport becomes the preferred option. If it is technically impossible or economically unfeasible to extend a railway line to the quarry field, an additional type of transport must be used to connect the quarry with the railway. This requires balancing environmental and economic efficiency criteria with the technical capabilities of the selected transport mode. The development and adaptation of innovative energy-saving transportation technologies, while simultaneously reducing the negative environmental impact, should be implemented under real industrial conditions. The study analyzed the transportation of raw materials from a quarry to one of the largest cement production plants. Analytical research and calculations were carried out to assess the energy consumption and carbon dioxide emissions when transporting marl by trucks, belt conveyors, and pipeline container transport from the quarry field to railway loading. The energy consumption for transporting one ton of raw material by trucks is 2.15 MJ. Over a year, trucks emit 820 tons of carbon dioxide. The energy consumption for transporting the same amount of raw material by belt conveyor is 1.52 MJ/t, with indirect carbon dioxide emissions of 406.4 tons per year under mixed electricity generation. When electricity is generated from renewable sources, emissions decrease to 50.8 tons. Studies on the gravitational movement of cylindrical containers have shown that pipeline container pneumatic transport ensures the lowest energy consumption for transporting mineral raw materials – 0.314 MJ/t. Indirect carbon dioxide emissions amount to 84 tons per year under mixed electricity generation and 10.5 tons when using renewable energy sources.

Keywords: low-carbon transition; transportation; mining raw materials; energy consumption; pipeline container pneumatic transport.

1. Introduction

Transport in mining production is a link in the technological process and its operation determines the efficiency of deposit mining and the reliability of raw material supply. The labor intensity of the process of moving rock mass is very high, and the costs of transport and related auxiliary work account for 45–50% of the total costs of raw material extraction. Various types of transport are used to move mineral raw materials from the deposit to the processing plant, the main of which are: railway, road and conveyor. The choice of rational transport for specific conditions depends on: physical and technical properties of mineral raw materials, transportation distance, terrain, development of transport infrastructure and communications [1].

The main advantages of rail transport include low specific energy consumption, the ability to provide almost any volume of cargo turnover at any distance of transportation. Road transport has high maneuverability and the ability to overcome significant differences in altitude. The main disadvantages of road transport are atmospheric pollution by exhaust gases, high energy consumption and operating costs [2]. The use of conveyor transport, along with a number of advantages, has disadvantages - the influence of climatic conditions on the operation of the conveyor, significant energy consumption and the complexity of operational maintenance.

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Based on real conditions, in order to optimize the route of raw materials, it is advisable to use combined transportation using different types of transport. At the same time, each type of transport, depending on the technical and technological parameters, is rationally used on a certain section of the route of raw materials.

Specific conditions for operating transport within the boundaries of the quarry field are economically advantageous overcoming of maximum elevations and minimum radii of route curves. In a first approximation, road transport meets these operating conditions. With a significant distance from the processing plant to the quarry, the use of rail transport is a priority.

If it is technically impossible or economically inexpedient to connect the railway to the quarry field, it is necessary to use an additional mode of transport to connect the quarry with the railway. In this case, it is necessary to determine the efficiency criteria and select the optimal mode of transport.

When transporting mineral raw materials, a balance is made between environmental and economic efficiency criteria and the technical capabilities of the selected mode of transport. The energy consumption of road transport is 4–12 times higher than that of a belt conveyor, and CO_2 emissions from transportation by cars are 3–10 times higher than from a belt conveyor [3–5].

Problem Statement. For a low-carbon transition of mining and mineral raw materials transportation processes, ensure a reduction in greenhouse gas emissions by reducing energy intensity with high economic efficiency.

2. Theoretical and experimental parts

Optimization of transportation of mining mineral raw materials from the quarry to the processing plant is an important task of increasing economic efficiency, reducing costs and environmental impact.

Mining enterprises have their own unique conditions for the development of deposits that distinguish them from each other, as well as different technical and economic indicators. The development and adaptation of innovative energy-saving technologies for transporting raw materials, while simultaneously reducing the negative impact on the environment, must be carried out in conditions close to a specific enterprise, which will contribute to obtaining correct results.

A typical marl quarry of one of the largest cement production enterprises was selected for research. Transportation of raw materials from the quarry to the cement plant is carried out in a combined way involving road and rail transport. Analyzing the supply of raw materials for 3 years, it was found that the maximum annual volume of transportation of raw materials from the quarry to the production enterprise is 2,168,000 tons.

The route of raw materials from the quarry to the plant is divided into 3 sections:

the first - intra-quarry transport; the second - from the quarry field to the loading area into railway cars; the third - the railway to the raw material warehouses of cement production.

In this study, we perform a comparative analysis of environmental, economic and energy efficiency criteria and technical capabilities of different types of transport at the *second* section.

Initial data: the distance of the second section in a straight line is 2.0 km, the length of the road is 2.2 km, the difference in geodetic heights is 31 m, the density of marl is 2,700 kg/m^3.

The transportation of marl is carried out by MAN 6×6 and MAN 8×8 vehicles. About 25 tons of raw materials are transported per trip. The estimated fuel consumption is 60–100 l/(100 km).

The maximum annual volume of raw material transportation by mass (M) is provided by 12 vehicles, which perform 86,720 trips. At the same time, according to regulatory indicators, they burn more than 350 thousand liters of diesel fuel. Total energy (Q) released during fuel combustion:

$$Q = V \cdot q,$$

where V – the volume of fuel, liters; q – the calorific value of diesel fuel, MJ/l.

Useful mechanical energy (W):

$$W = Q \cdot \eta,$$

where η – efficiency of the internal combustion engine.

At V = 350,000 l, q = 36 MJ/l, η = 0.37. We get W = $4.66 \cdot 10^9$ J.

Energy intensity (E) of transportation of 1 ton of raw material by car:

$$E = \frac{W}{M} = 2.15 \text{ MJ/t.}$$

CO_2 emissions from diesel fuel combustion are 2.68 kg/l (according to the International Energy Agency and EPA). Total emissions are about 820 tons of CO_2.

We determine the parameters and operating costs of a belt conveyor that transports raw materials from the quarry to the loading area into railway cars. There is a turn along the length of the route, so we divide the route into 2 equal sections, on which separate identical conveyors are installed at the appropriate angle of the route turn. The calculation diagram of such a conveyor is shown in Figure 1.

Input data: – transported cargo – marl, cargo density ρ = 2.7 t/m^3, productivity (Q_{bc}) – 320 t/hour, transportation velocity V = 1.0 m/s, l_1 = 400m; l_2 = 200 m; l_3 = 400 m; β = 0.5 degrees.

Calculations were performed using standard methods [6]. Conveyor belt width B_c = 650 mm. Running load from cargo weight q_B = 872N/m.

The value of the minimum allowable tension of the working branch S_{Pmin} = 11,183 N.

K_E – reserve ratio, K_E = 10 with a conveyor length of more than 100 m.

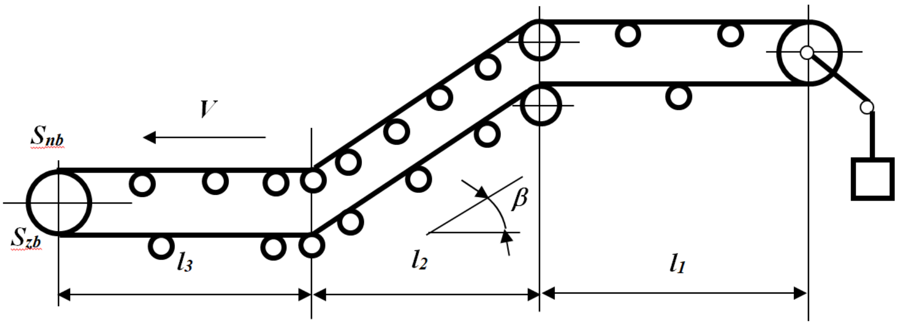


Figure 1 – Calculation diagram of a belt conveyor

The minimum tension of the working branch, according to the traction calculation – 17,901 N, which is significantly higher than the minimum permissible. The condition for ensuring the minimum tension is met.

The efficiency of the drive drum is 0.9. The calculated power value on the drive drum of the conveyor is 74,512 W.

The total power of the belt conveyor (P_{en}) is 150 kW.

Total conveyor operating time (t):

$$t = \frac{M}{Q_{bc}}.$$

Total energy consumed by the engine (W_{el}):

$$W_{el} = P_{en} \cdot t.$$

At M = 2,168,000 t, Q_{bc} = 320 t/hour, η = 0.9.

We get $W = 3.29 \cdot 10^{12}$ J = $1.016 \cdot 10^{6}$ kW·h.

The energy intensity of transporting 1 ton of raw materials by belt conveyor is E=1.52 MJ/t.

The average carbon footprint for electricity production from mixed generation [7] is 400 g CO_2/(kW·h), and for renewable energy [8] it is 50 g CO_2/(kW·h).

Total CO_2 emissions from transporting 2168000 tons of raw materials by belt conveyor from mixed generation of electricity are 406.4 t CO_2, and for renewable energy – 50.8 t CO_2.

Reducing energy intensity and, as a result, reducing CO_2 emissions can be achieved by using gravity transportation. The difference in geodetic heights ensures the movement of cargo under the action of its own weight. Consider the movement of mining raw materials using a pipeline container pneumatic transport [9], which belongs to the 5th generation transport [10].

The raw material is loaded into cylindrical containers that roll in a rectangular cross-section pipe installed at an angle α to the horizon. The containers move under the influence of gravitational forces, and if necessary, a driving force can be created using the pressure of the air flow in the direction of movement.

3. Results and discussion

Investigation of the gravitational motion of a cylindrical container.

A cylindrical container of radius R and mass m rolls, under the action of gravity, along an inclined plane that forms an angle α with the horizon (Fig. 2). External forces act on the container: gravity $\overline{G} = m \cdot \overline{g}$, normal pressure force of the plane on the cylinder $\overline{N}$, friction force of rolling a cylinder on a plane $\overline{F}_{tk}$, rolling friction moment $\tilde{M}_{tk}$ and the force of aerodynamic air resistance F_{ar}. The container performs plane-parallel motion: the center O moves translationally, and the container itself rotates around its own axis.

According to Newton's second law, write the equation of force equilibrium.

$$m \cdot \overline{g} + \overline{N} + \overline{F}_{tc} + \overline{F}_{tk} + \overline{F}_{on} = m \cdot \overline{a}, \qquad (1)$$

where $\bar{a}$ – the acceleration of the center of mass of the container along the inclined plane.

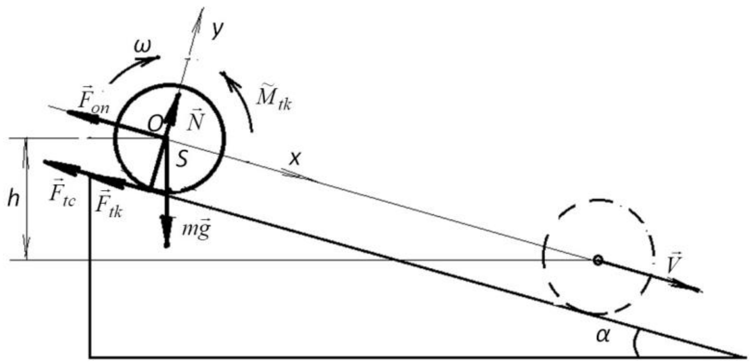


Figure 2 – Diagram of the gravitational motion of a cylindrical container during acceleration

We project this equation onto the x-axis

$$m \cdot g \cdot \sin\alpha - F_{tc} - F_{tk} - F_{on} = m \cdot a. \qquad (2)$$

Let us write the equation of equilibrium of the sum of moments about the axis of the cylindrical container from the forces acting on the cylinder

$$\sum M_o(F_i) = 0; \quad (F_{tc} + F_{tk}) \cdot R = J \cdot \varepsilon + M_{tk}, \qquad (3)$$

where ε – angular acceleration of the cylinder; J – moment of inertia of a solid cylinder, $J = {m \cdot R^2}/{2}$; M_{tk} – rolling friction moment, $M_{tk} = f_k \cdot N \cdot \cos\alpha = f_k \cdot m \cdot g \cdot \cos\alpha$; F_{tk} – rolling friction force, $F_{tk} = f_k \cdot \frac{N}{R} = \frac{f_k \cdot m \cdot g \cdot \cos\alpha}{R}$.

Let's write down $V = \omega \cdot R$; $a = \varepsilon \cdot R$; $\varepsilon = \frac{a}{R}$.

Here V – the velocity of the center of mass of the container; ω – the angular velocity of the container.

Then the friction force of the coupling F_{tc}

$$F_{tc} = \frac{J \cdot a}{R^2} - F_{tk} + \frac{M_{tk}}{R}, F_{tc} = \frac{J \cdot a}{R^2} - \frac{f_k \cdot m \cdot g \cdot \cos\alpha}{R} + \frac{f_k \cdot m \cdot g \cdot \cos\alpha}{R}.$$

Finally $F_{tc} = \dfrac{J \cdot a}{R^2}$.

The force of aerodynamic air resistance is determined by the formula [11]:

$$F_{ar} = \frac{C_x \cdot \rho \cdot A \cdot V^2}{2}, \quad (4)$$

where C_x – dimensionless drag coefficient; ρ – air density (ρ = 1.2255 kg/m^3) at normal atmospheric pressure and air temperature t = 18°); A – the diametrical cross-sectional area of the container.

We substitute the friction force of the clutch, the rolling friction force and the aerodynamic drag force into equation (2)

$$m \cdot g \cdot \sin\alpha - a \cdot \frac{J}{R^2} - \frac{f_k \cdot m \cdot g \cdot \cos\alpha}{R} - \frac{C_x \cdot \rho \cdot A \cdot V^2}{2} = m \cdot a,$$

$$g \cdot \sin\alpha - a \cdot \frac{J}{m \cdot R^2} - \frac{f_k \cdot g \cdot \cos\alpha}{R} - \frac{C_x \cdot \rho \cdot A \cdot V^2}{2 \cdot m} = a. \quad (5)$$

From equation (5) we determine the acceleration

$$a = \frac{g \cdot \sin\alpha - \dfrac{f_k \cdot g \cdot \cos\alpha}{R} - \dfrac{C_x \cdot \rho \cdot A \cdot V^2}{2 \cdot m}}{1 + \dfrac{J}{m \cdot R^2}}. \quad (6)$$

The path traveled by the container on an inclined plane

$$L = \frac{V^2 - V_0^2}{2 \cdot a},$$

where V_o – the velocity of the container at the beginning of the movement; V – the speed of the container at the end of the inclined plane.

At $V_0 = 0$, the acceleration of the container

$$a = \frac{V^2}{2 \cdot L}.$$

We substitute the acceleration into (5)

$$g \cdot \sin\alpha - \frac{f_k \cdot g \cdot \cos\alpha}{R} = \frac{V^2}{2 \cdot L}\left(1 + \frac{J}{m \cdot R^2}\right) + \frac{C_x \cdot \rho \cdot A \cdot V^2}{2 \cdot m},$$

$$V^2\left(1 + \frac{J}{m \cdot R^2} + \frac{C_x \cdot \rho \cdot A \cdot L^2}{m}\right) = 2 \cdot L \cdot g \cdot \sin\alpha + \frac{2 \cdot L \cdot f_k \cdot g \cdot \cos\alpha}{R} \quad (7)$$

From equality (7) we determine the speed of the container at the end of the inclined plane

$$V = \sqrt{\frac{2 \cdot L \cdot g \cdot \sin\alpha - \frac{2 \cdot L \cdot f_k \cdot g \cdot \cos\alpha}{R}}{1 + \frac{J}{m \cdot R^2} + \frac{C_x \cdot \rho \cdot A \cdot L}{m}}}. \quad (8)$$

According to formula (6) we calculate the acceleration of the container.

After the acceleration of the container, along an inclined plane, consider its movement along a plane with a counter-incline at an angle β (Fig. 3). At the beginning of the movement, the container has kinetic energy. The forces acting on the container are described above.

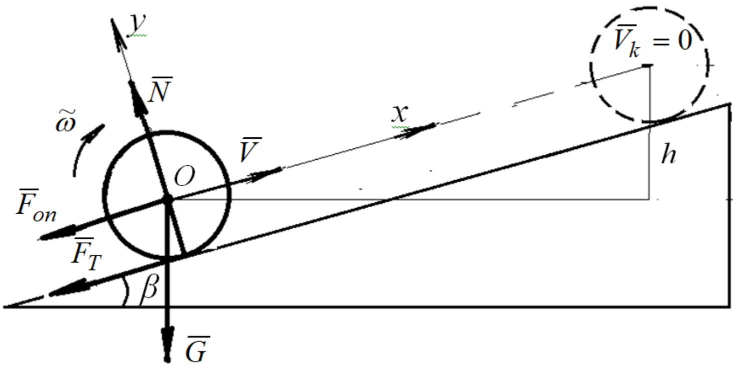


Figure 3 – Diagram of the motion of a cylindrical container on a plane with an opposing incline

We project equation (1) onto the x-axis

$$-m \cdot g \cdot \sin\beta - F_{tc} - F_{tk} - F_{on} = m \cdot a. \quad (9)$$

Here the friction force of the clutch

$$F_{tc} = \frac{J \cdot a}{R^2}.$$

The aerodynamic drag force is determined by formula (3).

Substitute the adhesion friction force, rolling friction force, and aerodynamic drag force into equation (9)

$$-m \cdot g \cdot \sin\beta - a \cdot \frac{J}{R^2} - \frac{f_k \cdot m \cdot g \cdot \cos\beta}{R} - \frac{C_x \cdot \rho \cdot A \cdot V^2}{2} = m \cdot a. \quad (10)$$

From equation (10) we determine the acceleration

$$a = \frac{-g \cdot \sin\beta - \frac{f_k \cdot g \cdot \cos\beta}{R} - \frac{C_x \cdot \rho \cdot A \cdot V^2}{2 \cdot m}}{1 + \frac{J}{m \cdot R^2}}. \quad (11)$$

The distance traveled by the containers during the period of speed change to the value V:

$$S = \frac{V^2 - V_n^2}{2 \cdot a} \quad \text{or} \quad a = \frac{V^2 - V_n^2}{2 \cdot S},$$

where V_n – the container speed at the beginning of the second section of movement; V–cylinder speed at the end of the section.

Taking into account (11), the path traveled by the container is

$$\frac{V^2 - V_n^2}{2 \cdot S} = \frac{-g \cdot \sin\beta - \frac{f_k \cdot g \cdot \cos\beta}{R} - \frac{C_x \cdot \rho \cdot A \cdot V^2}{2 \cdot m}}{1 + \frac{J}{m \cdot R^2}}; \quad (12)$$

$$S = \frac{\left(V^2 - V_n^2\right)\left(1 + \frac{J}{m \cdot R^2}\right)}{-2 \cdot g \cdot \sin\beta - \frac{2 \cdot f_k \cdot g \cdot \cos\beta}{R} - \frac{C_x \cdot \rho \cdot A \cdot V^2}{m}}. \quad (13)$$

If the container, after acceleration, moves horizontally (β=0), then it will pass the way

$$S_{hor} = \frac{\left(V^2 - V_n^2\right)\left(1 + \dfrac{J}{m \cdot R^2}\right)}{-\dfrac{2 \cdot f_k \cdot g}{R} - \dfrac{C_x \cdot \rho \cdot A \cdot V^2}{m}}. \tag{14}$$

From equality (14), we determine the container velocity V_k at the end of a given length of horizontal section of movement

$$V_{khor} = \sqrt{\frac{\left(1 + \dfrac{J}{m \cdot R^2}\right)V_n - \dfrac{2 \cdot f_k \cdot g \cdot S_{hor}}{R}}{\left(1 + \dfrac{J}{m \cdot R^2} + \dfrac{C_x \cdot \rho \cdot A \cdot S_{hor}}{m}\right)}}. \tag{15}$$

The kinetic energy of the container at the end of the horizontal section of motion

$$T = \frac{m \cdot V_k^2}{2} + \frac{J \cdot \omega^2}{2}, \tag{16}$$

where J –container moment of inertia; $\omega = V_k / r$ – angular velocity of the container at the end of the horizontal section of motion.

To completely stop the container, it is necessary to direct its movement upwards to a certain height. From the equality of kinetic and potential energies (T = Π), we determine the height of the container lift

$$\Pi = m \cdot g \cdot h; \quad h = \frac{T}{m \cdot g}. \tag{17}$$

Let's determine what the initial velocity should be V_{in} container after acceleration to overcome a horizontal section of movement of length S_{hor} and have, at the end of the section, speed V_{khor}.

In formula (15), we perform the permutations

$$\left(1 + \frac{J}{m \cdot R^2}\right) \cdot V_n^2 = \left(1 + \frac{J}{m \cdot R^2} + \frac{C_x \cdot \rho \cdot A \cdot S_{hor}}{m}\right) \cdot V_{khor}^2 + \frac{2 \cdot f_k \cdot g \cdot S_{hor}}{R}.$$

We rewrite the expression by substituting the value $J = {m \cdot R^2}/{2}$,

$$1.5 \cdot V_n^2 = \left(1.5 + \frac{C_x \cdot \rho \cdot A \cdot S_{hor}}{m}\right) \cdot V_{khor}^2 + \frac{2 \cdot f_k \cdot g \cdot S_{hor}}{R}.$$

From here

$$V_n = \sqrt{1 + 2 \cdot \frac{C_x \cdot \rho \cdot A \cdot S_{hor}}{3 \cdot m} \cdot V_{khor}^2 + \frac{4 \cdot f_k \cdot g \cdot S_{hor}}{3 \cdot R}}\,. \qquad (18)$$

Time to move the container along a horizontal section

$$t = \frac{V_{khor} - V_n}{a}. \qquad (19)$$

The rolling of the container along the horizontal part of the movement section is provided by the kinetic energy that it acquires while moving during acceleration down the inclined surface. Its speed, on this section of movement, is determined by the formula (8).

The geometric parameters of the inclined acceleration section are determined from the formula (8), which we rewrite as:

$$2 \cdot L \cdot g \cdot \sin\alpha - \frac{2 \cdot L \cdot f_k \cdot g \cdot \cos\alpha}{R} - \frac{C_x \cdot \rho \cdot A \cdot L \cdot V_n^2}{m} = \left(1 + \frac{J}{m \cdot R^2}\right) \cdot V_n^2. \qquad (20)$$

To determine the parameters of the inclined section of the movement L and α, we set the angle α and calculate the length of the section L

$$L = \frac{1.5 \cdot V_n^2}{2 \cdot g \cdot \sin\alpha - \dfrac{2 \cdot f_k \cdot g \cdot \cos\alpha}{R} - \dfrac{C_x \cdot \rho \cdot A \cdot V_n^2}{m}}. \qquad (21)$$

Container acceleration time

$$t = \sqrt{\frac{2 \cdot L}{a}}. \qquad (22)$$

According to formulas (14) and (21), we determine the path of gravitational motion of the container. These are the main geometric parameters when designing a transportation route. In this case, we specify the angle of inclination of the inclined plane of acceleration of the container.

The movement of the container is provided by the kinetic energy that it acquires in the acceleration section. Its movement in this section is uniformly decelerated with acceleration, which is determined by formula (11).

If the container is assumed to move uniformly, at a constant speed, then the forces of rolling friction resistance and aerodynamic air resistance will be balanced by the driving force from the weight of the container. The balance of these forces will be achieved if the track is inclined, in the direction of movement, at an angle β, which is determined by the equation obtained from expression (11), taking into account that the acceleration a=0.

$$-g \cdot \sin\beta - \left(\frac{f_k \cdot g}{R}\right) \cdot \cos\beta - \frac{C_x \cdot \rho \cdot A \cdot V^2}{2} = 0. \tag{23}$$

The obtained dependencies (13, 14, 21, 23) are an algorithm for determining the geometric parameters of the gravitational transportation route of raw materials in cylindrical containers.

For example, we determine the time of movement of a container with a mass of 6500 kg along a route 2000 m long due to the kinetic energy acquired when rolling along an inclined plane with an angle of inclination to the horizon of 10°. At the end of the container's movement, we set the speed to 1 m/s. The length of the inclined acceleration section determined by formula (21) is 8.42 m. The acceleration time determined by formula (22) is 3.94 s, and the horizontal movement time determined by formula (19) is 8.39 min. Thus, the approximate time of passage of the container along the entire path is 8.5 min.

With appropriate technical equipment and organization of loading and unloading operations [12], it is possible to obtain transportation performance similar to that of transportation by a belt conveyor. At a productivity of 320 t/h, the frequency of loading containers onto the route is approximately 50 containers per hour. At the same time, 9–10 containers move along the entire length of the route, which corresponds to the average normal operating mode of the equipment. Analysis of the study of the gravitational movement of a cylindrical container confirms the possibility of transporting mining raw materials in cylindrical containers due to their own weight without applying external forces. At the same time, by changing the angle of inclination of the route, it is possible to regulate the speed of movement in a wide range, to obtain different modes of movement: accelerated, slowed down and uniform.

With a full cycle of gravitational transportation of raw materials in cylindrical containers, there is a need for reverse movement of the container.

According to the obtained algorithm of gravitational movement, we calculate the geometric parameters of the route and the time of reverse movement of an empty container. An empty container with a mass of 550 kg must be moved along a horizontal surface 2000 m long using the kinetic energy acquired during acceleration along an inclined plane. At the end of the horizontal section of movement, we set the container to a speed of 1 m/s.

Calculated parameters.

Length of the inclined acceleration surface – 11.54 m.

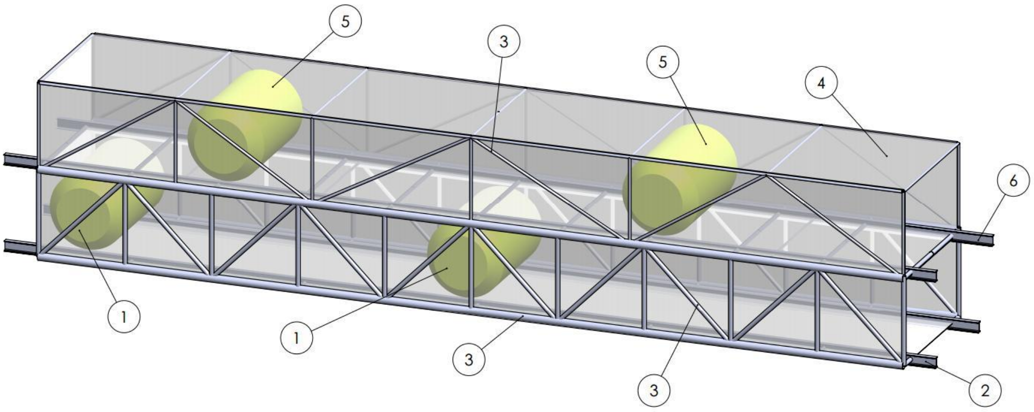
Container acceleration from a height – 2.0 m

Angle of inclination of the acceleration surface to the horizon – 10 degrees.

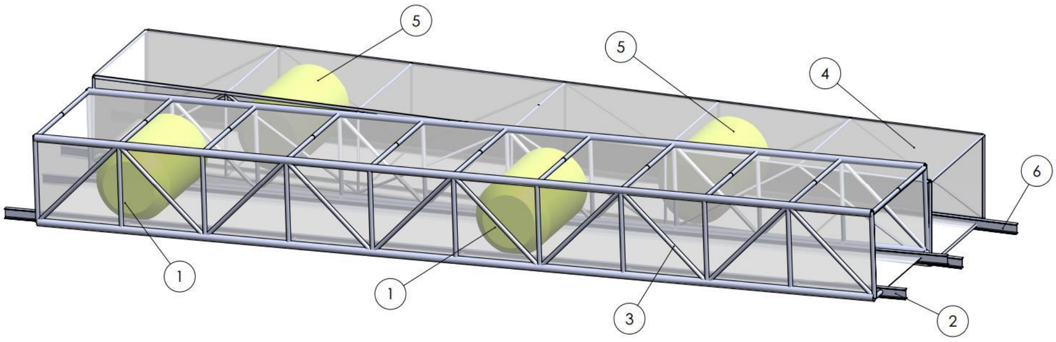
Acceleration time – 4.96 s.

Container horizontal movement time – 8.31 min.

The calculation method has established that the reverse movement of an empty container is also provided by gravitational movement. In the case of forward and reverse movements, almost 95% of the route can be horizontal. Thus, with low productivity, transportation in the forward and reverse directions can be carried out alternately along one route. In this case, the route should be equipped with appropriate acceleration sections in the forward and reverse directions of movement, as well as container capture sectors. In the case of high productivity, for the forward and reverse movement of containers, the routes should be separate. Variants of their relative placement are shown in Figure 4.



a)



b)

a) parallel routes for forward and reverse uniformly slowed container movements;
b) Non-intersecting arrangement of container movement routes;
1 – Loaded container; 2 – Guides for the forward movement of the loaded container;
3 – Supporting metal structure elements; 4 – Side walls of the pneumatic pipeline with a rectangular cross-section; 5 – Empty container; 6 – Guides for the return movement of the empty container

Figure 4 – General view of the relative arrangement of container gravity movement routes in the forward and return directions

When implementing uniformly slowed-down container movement in the forward and reverse directions, it is advisable to place horizontal sections of the tracks in one vertical plane in a common supporting structure (Figure 4, a). This achieves a relatively higher level of strength and rigidity of the supporting structure with less material consumption compared to the spaced placement of the tracks. If it is necessary to implement different modes of movement in the forward and reverse directions, the tracks are placed in different vertical planes (Figure 4, b), that is, they are parallel. When transporting raw materials by container pipeline transport, external energy is spent on performing work to raise the containers to the installation level at the beginning of the acceleration section. A filled container weighing 6,500 kg is raised to a height of 2 m. An empty container weighing 550 kg is raised to a maximum height of 30 m, which corresponds to the difference in geodetic heights of the gravitational movement tracks in the forward and reverse directions. It has been calculated that the energy intensity of transporting 1 ton of marl by pipeline container transport is 0.314 MJ. The lifting mechanisms are electrically driven, so CO_2 emissions depend on the type of electricity generation [7, 8]. Total CO_2 emissions during the year with mixed electricity generation are 84 tons, and with generation from renewable sources – 10.5 tons.

For comparative analysis, Table 1 summarizes the energy intensity and total CO_2 emissions when transporting 2,168,000 tons of marl by various modes of transport in the *second* section under study from the quarry to the loading site into railway cars.

Table 1 – Indicators of energy consumption and total CO_2 emissions of different types of transport

No	Type of transport	Energy source	Energy intensity, MJ/t	CO_2 emissions, t
1	Road transport	Internal Combustion Engine, diesel	2.15	820
2	Belt conveyor	Electricity, mixed generation	1.52	406.4
		Electricity, renewable sources	1.52	50.8
3	Pipeline container transport	Electricity, mixed generation	0.314	84
		Electricity, renewable sources	0.314	10.5

The results of the research showed that the pipeline container pneumatic transport is the most efficient in terms of energy consumption and CO_2 emissions. The full cycle of transportation of mining raw materials is ensured by gravitational movement.

If necessary, additional driving force is created by the pressure of air, which is pumped into the pipeline. Fundamental research of this process [10] was systematically carried out at the M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine.

4. Conclusions

If the processing plant is far from the quarry, transportation of raw materials by rail is a priority. If it is economically impractical to build a railway track to the quarry field, it is necessary to use an additional mode of transport to connect the quarry with the railway. To compare the efficiency of different modes of transport, studies of energy intensity and CO_2 emissions during the transportation of marl by road, belt conveyor and pipeline container pneumatic transport were carried out. The results of the studies showed that pipeline container pneumatic transport provides the minimum energy intensity of transportation of mining raw materials with minimal CO_2 emissions. The use of pipeline container pneumatic transport is an effective way of low-carbon transition in the transportation of mining raw materials.

Conflict of interest

Authors state no conflict of interest.

REFERENCES

1. Frolov, O.O. and Kosenko, T.V. (2020), *Vidkryti hirnychi roboty. Chastyna I. Protsesy vidkrytykh hirnychykh robit* [Open pit mining. Part I. Processes of open pit mining], KPI im. Ihoria Sikorskoho, Kyiv, Ukraine.

2. Bilichenko, M.Ia., Pivniak, H.H., Renhevych, O.O., Taoasov, V.I., Varshavskyi, A.M., Denyshchenko, O.V., Zrazhevskyi, Yu.M., Pryhunov, O.S., Troshchylo, B.C. and Shenderovych, Yu.M. (2005), *Transport na hirnychykh pidpryiemstvakh* [Transportation at mining enterprises], National Mining University, Dnipropetrovsk, Ukraine.

3. Razumova, K.M., Temchenko, O.A. and Shevchuk N.A. (2021), "Substantiation of the feasibility of using combined transportation technologies to ensure efficient development of iron ore deposits", Vcheni zapysky TNU imeni V.I. Vernadskoho, vol. 32, no. 5, pp. 270-278. https://doi.org/10.32838/2663-5941/2021.5/41

4. Liu, F., Cai, Q., Chen, S., and Zhou, W. (2015), "A comparison of the energy consumption and carbon emissions for different modes of transportation in open-cut coal mines", International Journal of Mining Science and Technology, no. 25 (2), pp. 261-266. https://doi.org/10.1016/j.ijmst.2015.02.015

5. Neradilova, H. and Stolarik, J. (2017), "RopeCon-progressive transportation system for continuous raw materials transportation", 17th International Multidisciplinary Scientific GeoConference SGEM, Albena, Bulgaria, 27 June - 06 July 2017, pp. 789-796. https://doi.org/10.5593/sgem2017/13/S03.100

6. Borysevych, B.D., Smaha, B.I., Senchishak, V.M. and Popovych V.Ya. (2004), Osnovy teorii i rozrakhunku zasobiv mekhanizatsii peremishchennia vantazhiv [Fundamentals of the theory and calculation of means of mechanization of cargo movement], Fakel, Ivano-Frankivsk, Ukraine.

7. Butrym, O.V. and Panchenko G.G. (2023) "Carbon footprint of electricity production", Energy Technologies & Resource Saving, vol. 77, no. 4, pp. 19-30. https://doi.org/10.33070/etars.4.2023.02

8. Wolfram, P., Wiedmann, T. and Diesendorf, M. (2016), "Carbon footprint scenarios for renewable electricity in Austral-ia", Journal of Cleaner Production, vol. 124, pp. 236-245. https://doi.org/10.1016/j.jclepro.2016.02.080

9. Kryzhanivskyi, Ye.I., Liakh, M.M., Mykhailiuk, V.V., Skrypiuk, R.B., Shymko, Ya.R. and Vytrykhovskyi, Ye.A., Ivano-Frankivsk National Technical University of Oil and Gas (2024), *Ustanovka truboprovidnoho konteinernoho pnevmotransportu* [Installation of pipeline container pneumatic transport], State Register of Patents of Ukraine, Kyiv, UA, Pat. № 157967.

10. Heiets, V.M., Voloshyn, O.I., Dzenzerskyi, V.O. and Nykyforuk, O.I. (2020), *Rozvytok ekonomichnykh ta naukovo-tekhnichnykh osnov transportu p'iatoho pokolinnia* [Development of economic, scientific and technical foundations of fifth generation transport], Kyiv, Ukraine.

11. Vakulenko, M.O. and Vakulenko, O.V. (2008), *Tlumachnyi slovnyk iz fizyky* [Explanatory Dictionary of Physics], Kyiv University Publishing and Printing Center, Kyiv, Ukraine.

12. Lavrukhin, O.V., Lomotko, D.V. and Aloshynskyi Ye.S. (2015), *Orhanizatsiia vykonannia vantazhnykh i skladskykh operatsii: navchalnyi posibnyk* [Organization of cargo and warehouse operations: training manual], Kharkiv, Ukraine.

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ШЛЯХИ НИЗЬКОВУГЛЕЦЕВОГО ПЕРЕХОДУ ПРИ ТРАНСПОРТУВАННІ ГІРНИЧОЇ СИРОВИНИ

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Анотація. У статті досліджено актуальну проблему глобального потепління — зменшення викидів парникових газів при транспортуванні мінеральної сировини від родовища до переробного підприємства. Для оптимізації маршруту руху сировини, доцільно застосовувати комбіновані перевезення з використанням різних видів транспорту. При цьому, кожен вид транспорту, в залежності від технічних і технологічних параметрів, раціонально використовується на певній ділянці маршруту руху сировини. Специфічним умовам роботи транспорту в межах границь кар’єрного поля відповідає автомобільний транспорт. При значній віддаленості переробного підприємства від кар’єру, використання залізничного транспорту є пріоритетним. При технічній неможливості або економічній недоцільності підведення залізничної колії до кар’єрного поля необхідно використовувати додатковий вид транспорту для сполучення кар’єру із залізницею. При цьому здійснюється балансування між екологічними та економічними критеріями ефективності і технічними можливостями вибраного виду транспорту. Розроблення і адаптація інноваційних енергозберігаючих технологій транспортування сировини, з одночасним зниженням негативного впливу на навколишнє середовище, необхідно здійснювати в реальних промислових умовах. Досліджували транспортування сировини від кар’єру до одного з найбільших підприємств цементного виробництва. Виконано аналітичні дослідження та розрахунки енергоємності і викидів вуглекислого газу при перевезенні мергелю автомобілями, стрічковим конвеєром та трубопровідним контейнерним транспортом на ділянці від кар’єрного поля до завантаження в залізничні вагони. Енергоємність транспортування однієї тонни сировини автомобілями складає 2,15 МДж. Протягом року автомобілі при цьому викидають 820 тонн вуглекислого газу. Енергоємність транспортування такої кількості сировини стрічковим конвеєром складає 1,52 МДж/т, а непрямі викиди вуглекислого газу при змішаній генерації електроенергії складають 406,4 тонни в рік. При генерації електроенергії відновлювальними джерелами викиди складають 50,8 тонн. Дослідження гравітаційного руху циліндричних контейнерів показали, що трубопровідний контейнерний пневмотранспорт забезпечує мінімальну енергоємність транспортування гірничої сировини – 0,314 МДж/т. При цьому непрямі викиди вуглекислого газу – 84 тонни в рік за змішаною генерацією та 10,5 тонн при генерації електроенергії відновлювальними джерелами.

Ключові слова: низьковуглецевий перехід; транспортування; гірнича сировина; енергоємність; трубопровідний контейнерний пневмотранспорт.