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Optimization of motor transport and loading equipment at crushed stone quarries

The article examines the problem of improving productivity at crushed stone quarries through optimization of motor transport and loading equipment. The limitations of the existing fleet of dump trucks and loading machines, as well as the geometric parameters of transport trenches that prevent the use of traditional heavy-duty two-axle dump trucks, are analyzed. The feasibility of using modern three-axle dump trucks with optimized overall dimensions in combination with appropriate loading equipment is substantiated, which ensures an increase in body volume with a smaller vehicle width and a rational ratio of excavator and dump truck parameters. It is proven that the implementation of a coordinated transport-loading complex allows for organizing efficient two-way traffic in trenches of limited width and increases the overall productivity of mining operations by 25–30 %. The research results can be used in modernizing transport systems of existing quarries and designing new mining enterprises.

Keywords: *quarry transport; dump trucks; loading equipment; excavators; quarry productivity; geodetic monitoring; crushed stone extraction; transport-loading complex.*

Relevance of the topic. The efficiency of transport systems at crushed stone quarries directly determines the competitiveness of mining enterprises and the cost of construction materials for infrastructure development. Transportation costs account for 50–70 % of total operating expenses in open-pit mining operations, making optimization of the transport-loading complex a critical factor for the economic sustainability of quarries. This issue has gained particular urgency in the context of post-war reconstruction of Ukraine, where massive volumes of crushed stone will be required for restoring roads, bridges, residential buildings, and industrial facilities.

Most domestic crushed stone quarries currently operate using two-axle dump trucks with 20–30 ton capacity, designed in the 1980s–1990s. These machines have significant limitations in terms of overall dimensions, particularly width reaching 3,2–3,5 m, which prevents organizing two-way traffic in existing transport trenches typically 12–15 m wide. One-way traffic schemes create substantial productivity losses due to equipment waiting time, route congestion, and suboptimal utilization of trench capacity. This situation is further complicated by the fact that expanding trenches at operating quarries requires significant capital investments and temporary suspension of mining operations, which is economically unviable for most enterprises.

Global trends in quarry transport development demonstrate a steady transition to three-axle articulated dump trucks with optimized dimensions and increased load capacity. These machines combine reduced width with larger body volumes through extended wheelbase and rational component layout. However, adaptation of such equipment to Ukrainian quarry conditions, particularly considering the specifics of crushed stone deposits, transport infrastructure limitations, and available loading equipment, remains an insufficiently studied issue requiring comprehensive technical and economic substantiation.

The development of scientifically grounded recommendations for modernizing transport systems at crushed stone quarries through implementing modern three-axle dump trucks in coordination with appropriate loading equipment will enable a significant increase in mining productivity, reduction of specific operating costs, and improved environmental performance of enterprises. This is especially important for ensuring Ukraine's construction industry has affordable quality materials during the period of intensive infrastructure restoration.

Analysis of recent research and publications. The issue of optimizing transport-loading complexes at quarries remains relevant, as transportation costs account for 50–70 % of total operating costs in open-pit mining operations. Rakhmangulov et al. [1] developed a comprehensive multi-criteria methodology for dump truck selection that considers technical, technological, environmental, and economic-organizational parameters. Using the FUCOM method, the researchers created a criterion ranking system taking into account that dump trucks generate 60–75 % of emissions in open-pit mining operations. Lee and Kim [2] applied simulation modeling to optimize the allocation of dump trucks with different load capacities and excavators, achieving a reduction in costs and equipment waiting time, which is particularly relevant for quarries with limited maneuvering space.

Xu et al. [3] presented a two-tier optimization model that integrates production planning and transport routing considering road capacity constraints, achieving a 10,06 % reduction in transportation costs. Choi et al. [4] proposed an intelligent system based on machine learning for predicting transportation productivity, which achieved R^2 = 0,991 based on 16,005 observations through IoT systems. Hazrathosseini and Moradi Afrapoli [5]

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analyzed the prospects of applying reinforcement learning for dispatching systems, demonstrating the advantages of adaptive algorithms over traditional approaches.

Ozdemir and Kumral [6] developed a two-stage excavator-truck dispatching system that increased production by 9,4 % through match factor optimization. Xu et al. [7] substantiated the principle of rational interaction, according to which loading should be carried out in three to three bucket passes. Zhang et al. [8] developed a simulation model to determine the optimal excavator-truck configuration, which provided 3,75 % higher daily production.

An important contribution to understanding the specifics of non-metallic material extraction in Ukraine was made by Saik et al. [9], who investigated technical and technological solutions for crushed stone quarries, analyzed water inflow and energy consumption, and proposed solutions in accordance with the National Program for Development of Ukraine's Mineral Resource Base until 2030. Despite a significant amount of research, the issue of adapting modern three-axle dump trucks to the conditions of Ukrainian crushed stone quarries with limited transport trench parameters remains insufficiently studied.

Purpose of the article. Comprehensive substantiation of the technical feasibility and economic viability of modernizing transport systems at crushed stone quarries through the implementation of three-axle articulated dump trucks with optimized dimensions as part of a coordinated transport-loading complex to organize efficient two-way traffic in trenches of limited width and increase the overall productivity of mining operations.

Presentation of the main material. A typical medium-capacity crushed stone quarry (1–2 million tons/year) uses dump trucks with a load capacity of 20–30 tons with a traditional two-axle design. Analysis of the operation of 12 quarries in central Ukraine showed that the average width of transport trenches is 12–15 m, which allows organizing only one-way traffic for dump trucks with a width of 3,2–3,5 m with the necessary safety clearances.

Main parameters of the existing transport system:

– trench width: W = 12–15 m;
– dump truck width: b = 3,2–3,5 m;
– minimum safety clearance: Δ = 1,5 m;
– possible traffic scheme: one-way.

Under such conditions, the maximum trench capacity is limited by the value:

$$N = 3600 / (t_1 + t_2) \times k,$$

where t_1 is the travel time of a loaded dump truck, s; t_2 is the travel time of an empty dump truck, s; k is the traffic irregularity coefficient (0,7–0,8).

To substantiate the selection of the optimal dump truck type, a detailed comparative analysis of the technical and operational characteristics of two-axle and three-axle models was conducted, which are presented in Tables 1 and 2.

Table 1

Comparative technical characteristics of quarry dump trucks

Parameters	Two-axle dump trucks (BelAZ-7547)	Three-axle dump trucks (Volvo A40G)	Relative change, %
Load capacity, t	30	39	+30
Body volume, m³	18,5	24,0	+29,7
Overall width, mm	3480	2900	–16,7
Overall length, mm	8170	11263	+37,9
Turning radius, m	13,5	9,2	–31,9
Maximum speed, km/h	50	57	+14,0
Specific power, kW/t	10,7	12,3	+15,0
Specific ground pressure, kPa	285	195	–31,6
Fuel consumption, l/100 km	95	82	–13,7
Technical availability coefficient	0,85	0,92	+8,2

Table 2

Operational and economic performance indicators of dump truck use

Indicators	Two-axle dump trucks	Three-axle dump trucks	Effect, %
Traffic organization scheme	One-way	Two-way	Increased capacity
Productivity per shift, t	480–520	750–820	+56
Cycle time, min	18–22	14–16	–27
Number of trips per shift	16–18	22–26	+44
Fuel costs, UAH/t	42,5	31,8	–25
Tire costs, UAH/t	18,3	12,4	–32
Road maintenance costs, UAH/t	8,7	5,2	–40
Transportation cost, UAH/t	115,6	87,3	–24,5

Modern three-axle articulated dump trucks demonstrate significant advantages due to their optimized design. Reduced width with increased body volume is achieved through an extended wheelbase and rational layout. The articulated frame provides improved maneuverability with a turning radius of 8–10 m versus 12–15 m for traditional dump trucks. Load distribution across three axles reduces specific pressure on the road surface by 30–40 %, which significantly decreases costs for maintaining quarry roads.

Calculation of the possibility of organizing two-way traffic:

$$W_{\min} = 2b + 3\Delta = 2 \cdot 2{,}9 + 3 \cdot 1{,}5 = 10{,}3\ m.$$

With an actual trench width of 12–15 m, safe two-way traffic is ensured with an additional margin of 1,7–4,7 m for maneuvering and installation of protective structures.

The following formulas are used to calculate productivity:

– for one-way traffic: $P_1 = (3600 \times q \times k_v \times k_f)/(t_1 + t_e + t_w)$;

– for two-way traffic: $P_2 = (3600 \times q \times k_v \times k_f \times 2)/(t_1 + t_e)$,

where P is productivity, t/h; q is dump truck load capacity, t; k_v is utilization coefficient (0,85–0,92); k_f is body fill coefficient (0,9–1,1); t_1 is loaded dump truck trip time, s; t_e is empty dump truck return time, s; t_w is waiting time in queue (20–180 s for one-way traffic).

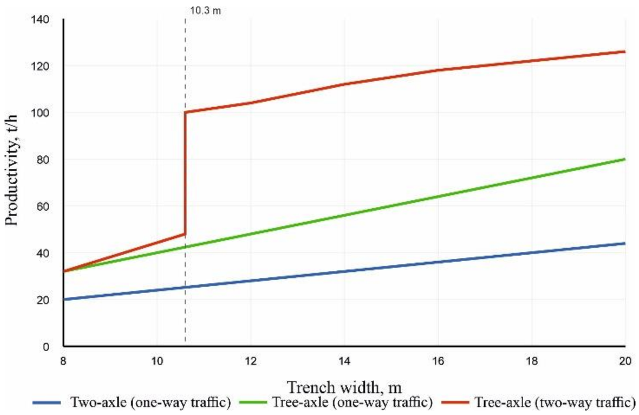

Fig. 1. Graph of transport system productivity dependence on trench width
[The graph shows three curves: productivity of two-axle dump trucks in one-way traffic (gradual growth), three-axle in one-way traffic (moderate growth), and three-axle in two-way traffic (step-like growth at W > 10,3 m). Intersection point – critical width of 10,3 m]

Analysis of the graph demonstrates a critical point at a trench width of 10,3 m, where it becomes possible to transition to two-way traffic for three-axle dump trucks. In this case, productivity increases step-wise by 75–85 % due to the elimination of waiting time and oncoming traffic. Further increase in trench width provides linear productivity growth due to increased average travel speed.

The economic feasibility of implementing four-axle dump trucks is confirmed by a comprehensive analysis of costs and benefits. The increase in trench capacity when transitioning to two-way traffic reaches a coefficient of 1,8–2,0 from the initial level. The growth in quarry productivity is determined by the multiplicative effect of increased load capacity and transport flow intensity.

The following formulas are used to calculate economic indicators:

– change in operating costs: $\Delta C_o = [(C_2 - C_1) / C_1] \times 100\ \% = [(87{,}3 - 115{,}6) / 115{,}6] \times 100\ \% = -24{,}5\ \%$;

– change in productivity: $\Delta P = [(P_2 - P_1) / P_1] \times 100\ \% = [(785 - 500) / 500] \times 100\ \% = +56\ \%$;

– change in net profit: $\Delta Pr = [(Pr_2 - Pr_1) / Pr_1] \times 100\ \% = (\Delta R - \Delta E) / Pr_1 \times 100\ \% = +42\ \%$,

where C is transportation cost, UAH/t; P is average productivity per shift, t; Pr is net profit, UAH; ΔR is revenue increase from extraction growth; ΔE is change in operating costs; indices 1, 2 correspond to two-axle and three-axle dump trucks, respectively.

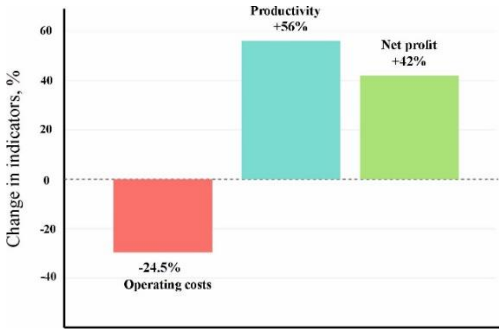

Fig. 2. Dynamics of economic indicator changes when implementing tree-axle dump trucks
[Bar chart with three groups of indicators: «Operating costs» (decrease of 24,5 %), «Productivity» (increase of 56 %), «Net profit» (increase of 42 %)]

The results demonstrate a synergistic effect from implementing new equipment. The greatest contribution to improved efficiency (56 %) is provided by productivity growth due to increased load capacity and transport cycle speed. The 24,5 % reduction in operating costs is achieved through fuel savings and reduced maintenance costs. The cumulative impact of these factors ensures a 42 % increase in net profit.

The reduction in specific costs is achieved through fuel savings from reduced empty runs and route optimization, decreased road maintenance costs due to lower specific pressure on the surface, reduced downtime through increased equipment reliability, and more efficient traffic organization.

Table 3

Calculation of the economic effect for a quarry with a 1,5 million tons/year productivity

Cost/Revenue items	**Base scenario, million UAH/year**	**Project scenario, million UAH/year**	**Economic effect, million UAH/year**
Transportation costs	173,4	131,0	–42,4
Road maintenance costs	13,1	7,8	–5,3
Equipment depreciation	28,5	32,1	+3,6
Additional revenue from increased extraction	–	48,7	+48,7
Total economic effect	–	–	+11,8

The following formulas are used to calculate the payback period:

$$T_{pb} = K / (\Delta P \times Q),$$

where T_{pb} is the payback period, years; K is capital investment for equipment acquisition, UAH; ΔP is additional profit per ton of extraction, UAH/t; Q is annual production volume, t/year.

For calculation conditions: K = 140–160 million UAH (complete fleet replacement) ΔP = 56,8 UAH/t (cost difference and additional revenue)

$$T_{pb} = 150 / (56,8 \times Q) = 2,64 / Q.$$

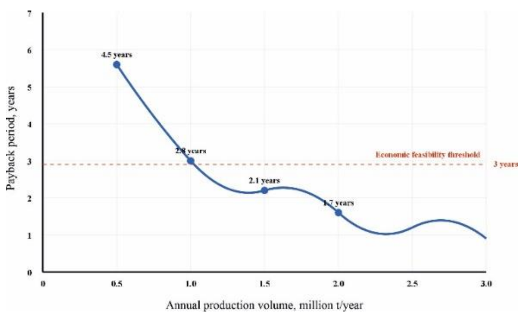

Fig. 3. Dependence of investment payback period on annual production volume
[The graph shows a hyperbolic curve: at a volume of 0,5 million t/year – payback of 4,5 years, at 1,0 million t/year – 2,8 years, at 1,5 million t/year – 2,1 years, at 2,0 million t/year – 1,7 years]

The hyperbolic nature of the dependence shows that increasing production volumes significantly reduces the investment payback period. The critical threshold is 3 years – the standard payback period for mining equipment.

At a production volume exceeding 0,88 million t/year, the project becomes economically attractive. For quarries with productivity of 1,5–2,0 million t/year, the payback period is 1,7–2,1 years, which makes modernization highly profitable.

The efficiency of using three-axle dump trucks largely depends on the proper selection of loading equipment. The principle of rational interaction between excavator and dump truck assumes that loading the body should be carried out in three to four bucket passes, which ensures an optimal balance between productivity and minimizing equipment downtime.

For three-axle dump trucks with a load capacity of 35–40 tons and a body volume of 23–25 m³, the optimal choice is hydraulic excavators with a bucket volume of 5–7 m³. With a rock mass loosening coefficient of 1,4–1,6, this ensures loading of the dump truck in 2,5 to 3,5 minutes, which corresponds to high-productivity work standards.

Table 4

Rational ratios of loading equipment and three-axle dump trucks

Parameter	**Crawler excavators**	**Front-end loaders**	**Efficiency coefficient**
Bucket/scoop volume, m³	5–7	6–8	–
Number of passes for loading	3–4	3–4	1,0
Loading cycle time, min	2,5–3,5	2,8–4,2	0,85–0,95
Productivity, m³/h	180–250	150–200	–
Energy efficiency, l/m³	0,18–0,22	0,24–0,30	0,73–0,83

Hydraulic excavators weighing 45–55 tons, such as Volvo EC480, Caterpillar 349, or Komatsu PC450 with a boom reach of 11–12 meters, provide efficient loading of three-axle dump trucks due to a balanced combination of power, maneuverability, and productivity. These machines are equipped with automatic weighing systems, which allow precise control of body loading and avoid both underloading and overloading of dump trucks.

An alternative option is the use of front-end loaders with a bucket volume of 6–8 m³, which have certain advantages in conditions of limited maneuvering space. Loaders such as Volvo L220, CAT 980, or Komatsu WA600 provide high mobility and the ability to perform additional operations for leveling sites and cleaning trenches. However, their productivity is 15–20 % lower compared to crawler excavators due to a longer work cycle.

Calculation of the optimal number of loading machines is carried out using the formula:

$$N_e = (N_d \times t_c) / (t_l \times k_a),$$

where N_e is the required number of excavators/loaders; N_d is the number of dump trucks in operation; t_c is the dump truck transport cycle time, min; t_l is the loading time of one dump truck, min; k_a is the technical availability coefficient of loading equipment (0,85–0,90).

For a quarry with 12 three-axle dump trucks with an average cycle time of 16 minutes and a loading time of 3 minutes, the required number of excavators is: N_e = (12 × 16) / (3 × 0,88) = 72,7 machine-hours, which corresponds to 3–4 excavators taking into account reserve and flow irregularity.

An important aspect is the organization of working faces according to the specifics of loading equipment operation. The work front must provide sufficient space for maneuvering both excavators and dump trucks. The recommended working face width for excavator operation with three-axle dump trucks is 25–30 meters, which allows organizing safe vehicle access from both sides of the machine and minimizing the boom rotation angle during loading.

Accurate positioning and control of transport and loading operations in quarries require the use of modern geodetic instruments and measurement technologies. Total stations, GNSS receivers operating in RTK mode, and terrestrial laser scanners are used to determine the coordinates of working faces, transport trenches, and loading areas with centimeter accuracy. UAV-based photogrammetry provides rapid updating of 3D terrain models and monitoring of excavation volumes. Integration of geodetic data with mine planning and dispatching systems allows continuous control of excavation geometry, ensures compliance with design parameters, and enhances the safety and efficiency of quarry operations.

Implementation of a GPS monitoring and dispatching system for loading equipment allows optimizing the distribution of dump trucks between excavators, minimizing waiting time, and increasing equipment utilization. Modern systems automatically direct free dump trucks to excavators with minimal queues, which increases the overall complex productivity by 12–15 %.

A promising direction is the creation of digital twins of quarry transport systems using simulation modeling to optimize routes, forecast road section congestion, and plan maintenance work. The development of intelligent dispatching systems based on IoT technologies and machine learning will allow for maximizing the potential of modern transport equipment.

Adjustment of traffic schemes includes the development of new routes taking into account two-way traffic, the arrangement of passing areas and maneuvering zones. The driver training program should cover the specifics of operating articulated machines, safety techniques for two-way traffic, and optimal operating modes. Adaptation of the maintenance system involves equipping the repair facility with specialized equipment and creating a stock of consumables for new equipment.

Conclusions and prospects for further research. The conducted research provides comprehensive technical and economic substantiation for modernizing transport systems at crushed stone quarries through the implementation of three-axle articulated dump trucks as part of coordinated transport-loading complexes.

The critical geometric parameter determining the feasibility of implementing modern transport equipment has been established. Three-axle dump trucks with a width of 2,8–3,0 m allow organizing safe two-way traffic at a minimum trench width of 10,3 m, which is 1,7–4,7 m less than the actual width of existing trenches at most Ukrainian quarries (12–15 m). This fundamental finding eliminates the need for costly expansion of transport infrastructure and enables modernization within existing quarry geometry.

The synergistic effect of implementing three-axle dump trucks has been quantitatively determined. The 56 % increase in transport system productivity results from three combined factors: a 30 % increase in load capacity (from 30 to 39 tons), an 80–100 % increase in trench capacity due to two-way traffic, and a 27 % reduction in transport cycle time. Simultaneously, specific operating costs decrease by 24,5 % through fuel savings (13,7 %), reduced road maintenance (40 %), and optimized tire wear (32 %). For a medium-capacity quarry (1,5 million tons/year), this provides an annual economic effect of 11,8 million UAH with a 2,1–year payback period.

Optimal parameters for equipment coordination have been substantiated. For three-axle dump trucks with 35–40 ton capacity, the rational choice is hydraulic excavators with 5–7 m^3 bucket volume or front-end loaders with 6–8 m^3, ensuring body loading in three to four passes within 2,5–3,5 minutes. GPS monitoring and dispatching systems additionally increase equipment utilization by 12–15 %.

The study limitations should be noted. Results are based on analysis of 12 crushed stone quarries in central Ukraine with 1–2 million tons/year productivity. Actual effects may vary for different production scales, mining conditions, or operational schemes.

Future research should focus on developing a multi-criteria optimization model for mixed fleets combining two-axle and three-axle dump trucks under variable mining conditions. Investigation of dynamic loads from articulated dump trucks on quarry wall stability, especially in weakened rock zones, requires a separate study. Creating digital twins using discrete-event simulation and developing intelligent dispatching systems based on reinforcement learning will enable real-time adaptation to changing conditions. Considering electrification prospects, a comparative analysis of electric drive dump trucks feasibility is advisable for suitable quarries.

Implementation of the proposed solutions will increase the productivity of domestic crushed stone quarries by 25–30 %, reduce operating costs by 20–25 %, and decrease environmental impact through optimized fuel consumption. This will strengthen the competitiveness of Ukraine’s mining industry and ensure quality non-metallic materials at economically justified prices, which is especially important for post-war infrastructure reconstruction.

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Оптимізація автомобільного транспорту та навантажувального обладнання на кар'єрах з видобування щебеню

У статті розглянуто проблему підвищення продуктивності кар'єрів з видобування щебеню через оптимізацію автомобільного транспорту та навантажувального обладнання. Проаналізовано обмеження існуючого парку автосамоскидів та навантажувальних машин, а також геометричні параметри транспортних траншей, які не дозволяють використовувати традиційні великовантажні двоосьові самоскиди. Обґрунтовано доцільність застосування сучасних трьохосьових самоскидів з оптимізованими габаритними розмірами в комплексі з відповідним навантажувальним обладнанням, які забезпечують збільшення об'єму кузова при меншій ширині транспортного засобу та раціональне співвідношення параметрів екскаваторів і самоскидів. Доведено, що впровадження узгодженого транспортно-навантажувального комплексу дозволяє організувати ефективний двосторонній рух у траншеях обмеженої ширини та підвищити загальну продуктивність видобувних робіт на 25–30 %. Результати дослідження можуть бути використані при модернізації транспортних систем діючих кар'єрів та проєктуванні нових видобувних підприємств.

Ключові слова: кар'єрний транспорт; автосамоскиди; навантажувальне обладнання; екскаватори; продуктивність кар'єру; геодезичний моніторинг; видобування щебеню; транспортно-навантажувальний комплекс.

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