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Prospects of Haulage Solutions for Mining Operations

Mark L. Khazin

Ural State Mining University (30 Kuybysheva st., Ekaterinburg, 620144, Russian Federation)

Направления развития карьерного автотранспорта

М.Л. Хазин

Уральский государственный горный университет (Россия, 620144, г. Екатеринбург, ул. Куйбышева, 30)

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Since the start of the civilization, people began to extract minerals from the surface of the Earth and transport the rock mass. Now the mining industry is striving for new haulage solutions for increasing amounts of rock masses from quarries, higher powers and carrying capacities of mining dump trucks. Today, we can assume that the revolutionary period of increasing the carrying capacity for heavy-duty dump trucks is over. Further designs improvements of frame dump trucks is not relevant. To create super powerful dump trucks capable of efficiently transporting the rock mass from deep horizons, it is necessary to offer absolutely different designs of machines and power plants. One of major requirements to new mining trucks is to minimize the negative impact on the environment. In its development, mining vehicles have come a long way: a hand wheelbarrow - a horse cart - a truck - a diesel mining dump truck - a diesel-electric mining dump truck - an electric mining dump truck - an unmanned electric mining dump truck. According to the law of the transition from quantity to quality, it can be assumed that the period of increasing the carrying capacity of mining dump trucks has ended (quantitative changes), and a new period of qualitative changes has begun (the development of new types of mining vehicles, an increase in the specific capacity of a power plant, the use of other energy carriers, etc.). The use of artificial intelligence is an important emerging area: robotic dump trucks, self-diagnostic systems, etc. New vehicles are expected to reduce the cost of transporting the rock mass and minimize the negative impact on the environment.

Ключевые слова:
карьерный самосвал, открытые горные работы, грузоподъемность, дизель, электропривод.

С начала возникновения цивилизации люди стали использовать добычу минералов на поверхности Земли и транспортировку горной массы. Одной из основных задач горнодобывающей промышленности является транспортировка все возрастающего количества горной массы из карьера, что вызвало необходимость повышения мощности и грузоподъемности карьерных самосвалов. На сегодняшний день можно полагать, что революционный период повышения грузоподъемности в создании большегрузных самосвалов закончился. Дальнейшее совершенствование конструкций рамных самосвалов нецелесообразно. Для создания сверхмощных самосвалов, способных эффективно транспортировать горную массу с глубоких горизонтов, необходимы принципиально другие конструкции машин и энергосиловых установок. Важнейшее требование к перспективным машинам – минимизация отрицательного влияния на окружающую среду. В своем развитии карьерный автотранспорт прошел длительный путь: ручная тачка – конная телега – грузовой автомобиль – дизельный карьерный самосвал – дизель-электрический карьерный самосвал – электрический карьерный самосвал – беспилотный электрический карьерный самосвал. Согласно закону перехода количества в качество можно полагать, что период повышения грузоподъемности карьерных самосвалов завершился (количественные изменения), и начинается новый период качественных изменений (разработка новых видов карьерного транспорта, повышение удельной мощности энергетической установки, применение других энергоносителей и т.п.). Важным направлением является применение искусственного интеллекта: роботизированных самосвалов, систем самодиагностики и др. Основное требование к перспективным машинам – уменьшение затрат на транспортировку горной массы и минимальное негативное влияние на окружающую среду.

Mark L. Khazin (Author ID in Scopus: 6506526940) – Doctor of Engineering, Professor of the Department of Mining Equipment Operation (tel: +007 343 283 09 56, e-mail: Khasin@ursmu.ru).

Хазин Марк Леонтьевич – доктор технических наук, профессор кафедры эксплуатации горного оборудования (тел: +007 343 283 09 56, e-mail: Khasin@ursmu.ru).

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Introduction

Various types of vehicles are used to transport the rock mass in quarries and mines, and a motor vehicle is the most commonly used facility [1]. In its development, mining vehicles have come a long way: a hand wheelbarrow - a horse cart - a truck - a diesel mining dump truck - a diesel-electric mining dump truck - an electric mining dump truck - an unmanned electric mining dump truck.

As you know, the first version of a mining dump truck was developed back in 1930 in Cleveland (Ohio, USA) by *Euclid Road Machinery*, which was an off-road truck with a bucket body with rear unloading and a cover that protected the driver's cab from bulk materials.

The technology of mining operations, such as an increase in the depth of quarries and haulage distances resulted in progressive carrying capacities of mining dump trucks. Over the past time, from 1930 to 2020, the carrying capacity of mining dump trucks has increased almost by 56 times, from 8 to 450 tons (Fig. 1).

At the same time, the environmental damage caused by such vehicles has also grown. Therefore, at present, the problem of reducing the negative environmental impact of mining machinery and equipment is becoming more and more urgent [5–7].

Any material system develops in a way, when quantitative changes at a certain stage lead to qualitative changes, so a new quality gives rise to new opportunities and periods of quantitative changes. According to the law of the transition from quantity to quality, it can be assumed that the period of increasing the carrying capacity of the mining dump trucks has ended (quantitative changes) and a new period of qualitative changes has begun (the development of new types of mining vehicles, an increase in the specific capacity of a power plant, the use of different energy carriers, etc.), and a new quality gives rise to new opportunities and periods of quantitative changes.

Upgrade of Diesel Engines

The power of the diesel engines grew as the carrying capacity of the mining dump trucks increased, no matter if it was used as a power plant for a dump truck or as a power source for an electric generator (Fig. 2). Thus, it entailed bigger masses and dimensions of the engine, the volume of consumed fuel and exhaust gases.

Diesel power of modern mining dump trucks (Caterpillar, Komatsu, Hitachi-Euclid, Terex, Liebherr, BelAZ) generally does not exceed 2000 kW with a carrying capacity of no more than 250 tons. For mining dump trucks with a larger carrying capacity, either two engines or engines with increased dimensions (with the number of cylinders 18, 20) are used [8].

Mining companies want to reduce operating costs by cutting diesel costs. Also, according to new environmental regulations, more fuel efficient and low-emission diesel engines had to be made. ACERT Engine Thermal Management and APES Transmission Management [9] improve the overall engine performance, reduce the level of fuel consumption, pollutant emissions and warm-up times. Nevertheless, up to 30 % of the fuel is still consumed for energy dissipated in the environment [10]. The present mining truck engines used by major manufacturers are Tier II - Tier III (Stage II - Stage III) compliant. The latest models of BelAZ dump trucks are equipped with Cummins engines, which meet international standards in terms of environmental requirements.

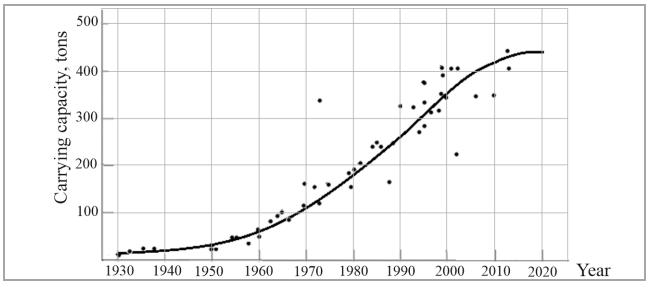

Fig. 1. Changing carrying capacities of mining dump trucks (as per data [2–4])

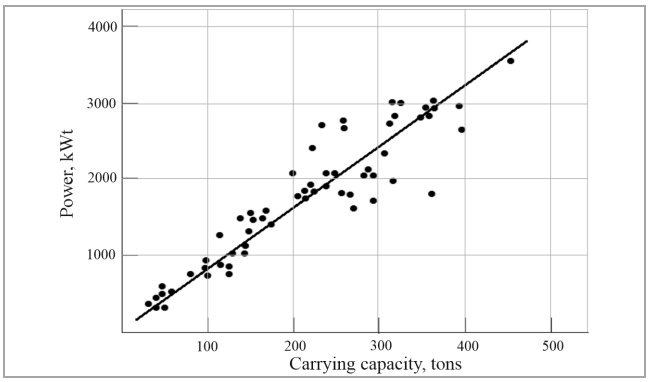

Fig. 2. Increasing powers of power plants depending on the carrying capacity of a mining dump truck

Energy Carriers

Diesel fuel. An intensive open-pit mining development in the first half of the 20th century increased the number of deep and superdeep quarries [1, 11] and, consequently, the distance traveled by dump trucks. As a result, the operating costs of mining operations increased due to higher consumptions of fuel and tires [12, 13]. Depending on the operating conditions, a typical mining dump truck consumes from 50 to 100 thousand liters of diesel fuel per year and emits from 130 to 260 tons of CO_2 in the exhaust gases. Billions of liters of diesel fuel are consumed annually to transport rock mass around the world.

Overhead lines. New options for mining companies to lower diesel costs and thereby lower operating costs has led to a renewed interest in overhead lines.

Electric dump trucks equipped with pantographs (trolley-trucks) can receive energy directly from the overhead line. The cost of the infrastructure, which includes an overhead line system, traction substations, high voltage line masts, a sag system lighting and a dump truck pantograph [13–16 is approximately 75 % of the price of a trolley-truck.

The use of power from an overhead line allows reducing the weight of the dump truck by 10-15 % by eliminating the diesel engine, fuel and oil tanks, oil and water radiators, exhaust systems and a number of other parts while maintaining the same carrying capacity.

The use of trolley-trucks can significantly reduce or eliminate the cost of purchasing, transporting and storing diesel fuel, increase the speed of the dump truck by 44 %, reduce the transportation time by 16 %, reduce the cost of airing quarries and save about 85 % of fuel at each working cycle [6, 12-16].

Compared to a dump truck, the main energy advantage of a trolley-truck is the option of recuperating kinetic energy into the line, which is released during braking and potential energy when driving downhill.

However, this technology has some disadvantages, such as high capital costs, limited mobility and operational flexibility.

To start work, it is necessary to lay a trolley line, and as the minerals are developed and the quarry grows, the line is to be extended with new sections. Trolley-trucks also require wider maneuvering spaces than comparable diesel vehicles. In this case, the line should be 300-600 m away from the place where the explosions are made. In addition, the high-voltage wires are close enough during the loading and unloading of a trolley-truck, and there is a risk of damage.

Trolley-trucks are a good alternative for underground and mining trucks, especially when working on long ramps. The best results can be achieved if the rock mass is moved over distances exceeding 1500 m, especially when the overhead line can be used for several years and the volume of the transported rock mass is more than 500,000 tons per year. According to the calculations [6, 12–16], the payback period of the system is 1–2 years taking into account the increased productivity of dump trucks in the overhead line. In addition, the environmental damage is significantly reduced, since there are no exhaust gas emissions, gas contaminations and fogs in a quarry or mine. Safety precautions for the operations and maintenance of electrified road and railway mining vehicles are similar.

Fully electric dump trucks. Today, there is interest in fully electric dump trucks, so a vehicle is already designed for an electric motor in order to maximize all its advantages [7]: versatility, energy efficiency, good tractive effort (including high torque at low speeds), no harmful emissions, reduced ventilation requirements, reduced operating costs, good overload capacity, less maintenance and higher productivity. Unfortunately, their mobility is still limited by the small capacity of batteries: lead-acid batteries have about 144 kJ/kg, and a battery based on lithium iron phosphate (LiFePO4) or LFP offers 396 kJ/kg. More efficient lithium-ion batteries have a capacity of up to 900 kJ/kg [17], but they are not yet used for vehicles.

Battery powered loaders are manufactured by the Canadian company *RDH Mining Equipment*. Loader Muckmaster 300EB with a bucket capacity of 2 m^3 and Haulmaster 800-20EB, which is a twenty-ton truck, are powered by an LFP battery. Since 2013, four Muckmaster 300EB and one Haulmaster 800-20EB have been operated at the Macassa gold mine (Makassa) - Lake Kirkland, Ontario, Canada [17]. According to RDH Mining Equipment, LFP batteries enable the loaders and trucks to operate on average for 4 hours, which is less than a work shift, usually ranging from 8 to 12 hours.

A Chinese concern BYD Co. developed a three-axle mining dump truck with a gross weight of 60 tons, an overall width of 3.2 m and an effective body volume of 30 m^3. The BYD V60 dump truck with a 6×4 wheel arrangement is designed to work in coal mines, as well as poorly aired open quarries. The traction motors and batteries are already designed for 10 tons, therefore, with a full weight, the 60 t lifting capacity of the vehicle is 30 t in total. The next and improved vehicle is the Swiss model called the Lynx truck with the carrying capacity of 65 t designed on the basis of Komatsu HD 605-7 diesel dump truck. Electric motors of the dump truck with a capacity of 590 kW are powered by rechargeable nickel-cobalt-manganese batteries with a total capacity of 700 kWh and a weight of 4.5 tons. The regenerative braking system of such a dump truck allows recharging the batteries by 40 kW·h. Therefore, during operations, such a 110-ton dump truck does not only consume electricity, but also powers the line with up to 200 kW of generated energy. During the period of operations at the Chasseral cement quarry (Switzerland) since the end of 2017, these vehicles have shown high profitability due to fuel saving and no carbon dioxide emissions [18, 19].

Compared to the vehicles with internal combustion engines, these ones have certain disadvantages, such as a short service life of batteries and a short driving distance. Other disadvantages of batteries include their costs (the storage of 1 W·h costs about 1 euro) and their heavy weight [20]. However, it is possible to recycle batteries after the end of their service life.

Using gas as a motor fuel. Natural gas is the main alternative fuel, which does not wash off the oil film from the cylinder walls and does not form precipitations in the fuel system. As a result, friction and wear of the engine decreases with an increase in its service life by 1.5–2 times, and the noise level is also reduced by 50 % [21, 22]. In addition, the emissions of pollutants from gas engines are 1.5–5 times less hazardous than from diesel engines, which is especially important for deep quarries. Another advantage of gas compared to diesel fuel is its significantly lower costs.

BelAZ-Holding has designed a BelAZ-75476 dump truck with a carrying capacity of 45 tons and a 404 kW Kungur-550 gas piston engine using liquefied natural gas (LNG). At the same time, the gas dump truck is more economical than the diesel analogue BelAZ-7547, it is 10 % more powerful and provides a low level of emissions of harmful substances. At present, a 136-ton BelAZ-7513 mining dump truck with a Cummins KTA50-C gas piston engine is being designed for production.

China launched the HOWO mining dump truck (manufactured by Sinotruk factory) and the F3000 series LNG tractor. The test results showed a twofold saving on fuel in monetary terms [23].

Tests of Caterpillar 777 and 793 dump trucks, Komatsu 830 and 930 using compressed natural gas in the US and Canadian mines have shown that the efficiency and performance of the gas engine is comparable to that of a diesel one.

It helped to save diesel fuel by 80 %, and the volume of exhaust gas emissions was reduced by 25 %, as well as improve the environmental situation [22].

Although the system developed by Caterpillar has been successfully tested in severe conditions of the Canadian climate, but due to high prices for the gas-fuel equipment, this project was not economically viable. GFS Corp. has achieved the best results in production of gas engine facilities for mining dump trucks.

Since 2015, Kovdorsky Ore Mining and Processing Plant and Kuzbass have started switching to production of mining dump trucks using compressed natural gas (CNG). It is expected that this will reduce the fuel costs, i.e. coal, by 30–40 % and reduce the negative impact on the environment [24].

Since 2015, ALROSA, OJSC has also been actively introducing a system for converting equipment to gas fuel. For example, in Yakutia district, where fuel has to be delivered a year in advance and only during the navigation period, which significantly increases its costs. Whereas the gas fields are located close to the ALROSA mine, the company relies on both replacing diesel engines of operated dump trucks with gas ones, and supplying dump trucks with gas engines. By using gas as a motor fuel, the company expects savings on fuels and lubricants of up to 100 million rubles per year [25].

Fuel cells and hydrogen. Fuel cells have no moving parts, they are durable, reliable and easy to operate. Even now, the efficiency of fuel cells is 50–70 %, which is much higher than that of an internal combustion engine, and is an important advantage over modern petroleum-fueled engines [26, 27]. The hydrogen engine is one of recent advances in this area. Unlike petroleum energy sources, hydrogen does not have harmful emissions into the atmosphere and is the most environmentally friendly, as only water is released.

Compared to lead-acid batteries, which are used in most electric drives today, hydrogen fuel cells do not need frequent and prolonged battery charging. It is enough to monitor hydrogen in the system and refuel it.

Nuvera company (Massachusetts, USA) specializes in production and distribution of hydrogen fuel cells used for Yale electric forklifts. Sandia National Laboratories/CA has developed an underground transport tractor that is powered by a proton exchange membrane fuel cell stack combined with a reversible metal hydride battery. During the tests, the tractor showed a low noise level and high environmental friendliness [27].

At the end of 2017, Toyota presented a hydrogen-powered truck prototype and tractor unit based on Kenworth T660. The truck is powered by two electric fuel cells from the Toyota Mirai light sedan, and the tractor unit consists of 740 battery fuel cells Panasonic with a capacity of 12 kW·h, providing a power of 500 kW [28].

In addition to obvious advantages, hydrogen fuel cells also have disadvantages. The first one is a high cost of platinum group metals. The second one is the weight and dimensions that exceed the corresponding parameters of available internal combustion engines due to a greater number of necessary components and assemblies. In addition, their manufacturing technology has not yet been fully developed. The third problem is the lack of hydrogen refueling.

However, this area has been progressing and new solutions to these problems are appearing. Soon, hydrogen will be able to replace gasoline, diesel and gas, and fuel cells will be used as the main power unit of mining dump trucks [29].

Multi-Wheeled Vehicles, Multi-Axle Vehicles and Long-Haul Trucks

Today, a further increase in the carrying capacity of mining dump trucks is limited by the carrying capacity of used tires and engine powers. Multi-wheel and multi-axis opportunities offer solutions, which solve the following problems:

1) more evenly distribute the load on the road to work on weak soils;

2) provide maneuverability in hard-to-reach areas, since such a vehicle can turn almost on the spot;

3) continue driving even if several tires are damaged.

Structurally, a multi-axle vehicle can be with fixed and rotary axes. For example, such a design enables the use of double wheels on each axle (the total number is 8) and a carrying capacity of 450 tons for the BelAZ-75710 dump truck.

The Chinese company Wuhan Sanjiang Import&Export Company Limited (WSIEC) produces a multi-wheeled dump truck WTW 220E with a carrying capacity of 220 tons and an own weight of 168 tons with a Cummins KTA38-CC diesel engine, which has 16 wheels located on eight semi-axles. 12 of the 16 wheels have their own 110 kW electric motor powered by the main generator.

It is logical that a long-haul truck development is underway in this new direction. ETF Company has developed the MT-240 mining dump truck (Fig. 3) on a four-wheel drive chassis with all five steerable pairs of wheels. The modular design allows you to create a wide range of dump trucks with various numbers of driving axles from 2 to 5 axles or more with a carrying capacity from 80 to 240 tons. By combining (coupling) several such vehicles into a single long-haul truck, the carrying capacity of MT-240 can be increased to 870 tons [30].

The wheel-to-wheel movement technology of long-haul trucks and the use of special devices guarantee their safe movement downhill eliminating the risk of folding the trailer part of the truck.

Multi-section coupled mining dump trucks (long-haul trucks) have a number of important advantages over classic two-axle heavy vehicles: transporting the rock mass for long distances (20-200 km) at a high average speed. The carrying capacity of a long-haul truck can be adjusted by connecting additional dumping sections and even by coupling an additional traction unit. A positive experience in operating Scania multi-section long-haul trucks was gained at the Udachny Ore Mining and Processing Plant [31, 32]. Fuel savings were approximately 25 % with a 12 % increase in productivity and a 20–35 % reduction in transportation costs. Also, it decreased the amount of exhaust gases, so improved the environmental conditions. Such indicators give mining companies not only environmental benefits, but also reduce the costs of transporting rock mass. Therefore, the use of long-haul trucks has proved to be one of the most promising areas for mining haulage advancements.

In general, this category of vehicles also has disadvantages: it is more difficult to repair, and when working in difficult conditions, the risk of failure of complex elements of the chassis increases. Nevertheless, this type of mining haulage is gaining popularity. Currently, long-haul trucks are produced by several companies: ETF Trucks, Scania, Volvo, Powertrans, TONAR.

Gas Turbine Dump Trucks

The main advantages of a gas turbine engine (GTE) are low specific mass (0.25–0.30 diesel mass), simplicity of design, almost no oil consumption, easier starting in winter conditions, low fuel consumptions in a steady state (1.4 times less than that of a diesel engine), etc. All this was demonstrated back in 1969 by a 120-ton truck BelAZ-549V with a gas turbine engine (GTE) having a capacity of 1200 l/h. But all these advantages of the GTE were eliminated by one disadvantage, as in transient modes (acceleration-deceleration), the fuel consumption was huge.

However, over the past 50 years, new materials and technologies have appeared in engine building. As a result, recently there has been a renewed interest in the use of gas turbine engines for vehicles [33–35].

A high efficiency of a diesel engine is generally known, but this statement is not absolute and is largely determined by operating conditions. For example, when the temperature decreases from +20 to –20°C, the minimum specific fuel consumption of the GTE called GAZ-902 decreases by more than 10 %, while the fuel consumption of a diesel engine, on the contrary, increases by 8–10 % [36].

Fig. 3. Mining dump truck MT-240 [30]

Modern models of gas turbine engines of automobiles have a specific fuel consumption of 200–270 kg/kW·h [33–37], which is comparable with the performance of a diesel engine. Studies [33] have shown that such gas turbine engines can be used for powerful off-road vehicles, including mining dump trucks. This opportunity became real thanks to BelAZ-75476 mining dump truck with a carrying capacity of 45 tons with a Kungur-550 gas turbine engine developed on the basis of the YaMZ-240NM2 engine of an increased power (550 l/h versus the standard 500 l/h). Since April 2018, BelAZ-75476 has been working at Nevyanskiy Cementnik, JSC (Sverdlovsk Region).

A serial industrial mining dump truck BelAZ with a carrying capacity of 90 tons has already appeared on sale. The gas turbine engine GTD-1250 with a capacity of 1250 l/s is used as its power plant (920 kW), produced by Kaluga Engine, PJSC [38]. The engine has a mass of 1,050 kg and a specific fuel consumption of 225 g/l and a significantly lower level of toxic emissions.

Vehicles with a Combined (Hybrid) Power Plant

When the depth of quarries increases, the average weighted slope of the roads and the distance of transportation increase, then the loads on the power plant and the transmission of a dump truck increase too. At the same time, the travel time of an empty dump truck increases and, consequently, the time of *unproductive* operations of the internal combustion engine at partial loads. In auxiliary operations of the transport cycle (accounting for 40–60 % of the travel time), the fuel consumption is 5–15 % of the total consumption for the transport cycle [39].

A hybrid or combined power plant (CPP) is one of good options aimed at saving fuel, which combines a traditional diesel or gasoline engine with an onboard rechargeable energy storage system, operated independently and sequentially [7, 14], for example, diesel trolley-trucks. Meanwhile, an internal combustion engine can be smaller, lighter and more efficient than a conventional dump truck because it is calculated on average energy consumptions rather than peak values. A high torque of a diesel engine combined with the hybrid technology can provide a significantly higher mileage. Moreover, an electric motor is mainly powered by a battery, and the internal combustion engine is used to charge the battery and to obtain maximum traction and speed indicators during acceleration, driving at high speeds and in difficult road conditions. Modern hybrid electric vehicles extend the charge of their batteries through regenerative braking.

In African countries, in Brazil, the USA and Europe, a transport system with the use of diesel trolley-trucks has been successfully operated for a long time. In particular, the example of the Betze gold mine (USA, Nevada) is worth mentioning, where for the transportation of 410 thousand tons of rock mass, a fleet of 73 diesel trolley-trucks with a carrying capacity of 170 tons is used per day.

Trolley-trucks are successfully operated at the Grootegeluk coal mines in South Africa [13–15] and Grivice at RMU Banovici in Bosnia-Herzegovina [16]. For the transportation of coal, mining trolley dump trucks with a lifting capacity of 254 tons of the Euclid-Hitachi EH4500 AC type are used. In March 2013, at the largest copper mine in Africa, Kansanshi (Kansanshi), the diesel vehicle fleet was completely replaced by Hitachi EH3500ACII trolley-trucks.

Currently, diesel trolley-trucks are produced by many manufacturing companies: Hitachi, Komatsu, Caterpillar, Liebherr and BELAZ.

Crawler Dump Trucks

A gradual development of flat-type mineral reserves results in a transition to upland-type deposits, located mostly in undeveloped areas. Upland quarries, such as the Molodezhnoe deposit of asbestos raw materials, experience significant difficulties in performing various jobs on steep slopes, which cannot be climbed by conventional mining vehicles.

For effective operations in severe mining conditions, it becomes necessary to create an absolutely new type of mining haulage, e.g. a crawler dump truck with a body on a rotating platform. The crawler drive allows the crawler dump truck to successfully transport the rock mass from an excavation site to reloading areas or warehouses. Its main advantages (in comparison with wheeled ones) are [39, 40]:

- high traction and coupling characteristics to overcome steep slopes (up to 35 %) at nominal operating conditions of the engine and transmission at relatively high travel speeds;
- high off-road characteristics and adaptability of the caterpillar track of the dump truck to bad roads, which makes it possible to completely eliminate the costs of its preparation and special coating;
- high maneuverability ensures the minimum time to exchange a dump truck for loading and unloading;
- relatively low specific ground pressure will provide a safer movement along narrow transport routes.

The design of the crawler dump truck provides a reduction in its width, compared to existing models of mining dump trucks, which makes it possible to reduce the width of roads in the quarry and reduce the amount of overburden.

Along with the main functions, the crawler dump truck can perform various auxiliary operations: towing equipment, evacuating stuck vehicles, and delivering workers. There is a prospect of creating a family of unified vehicles on a single tracked chassis, including, in addition to a dump truck, a drilling rig, a tow truck, a road construction vehicle, a mobile workshop and a service vehicle (for maintenance and repairs), a conveyor for transporting people and other equipment.

Crawler dump trucks used to develop low-power and close to the surface of the ore bodies will allow the excavation and development of a steeply inclined common capital trench for the entire depth of the quarry without separating the sides.

Today, a number of foreign companies are engaged in the production of crawler vehicles: Hitachi Construction Machinery Co. Ltd., Komatsu, Morooka Co. Ltd, Sunbelt Equipment Marketing, Inc. (SEMI), Mitsubishi, Richard Larrington Ltd and others. The vehicles of these manufacturers have rubber-metal crawler tracks and are designed for the transportation of goods and building materials on weak soils. They are distinguished by good maneuverability, speed of moving goods, most of the parts are unified with hydraulic excavators of the corresponding manufacturers. However, the presented samples of foreign tracked vehicles were designed and manufactured with no account for complex mining conditions of quarries, therefore, their use as mining haulage is not possible.

FSUE KBTM (Omsk), FSUE UKBTM (Nizhny Tagil) presented their design proposals for tracked dump trucks with a carrying capacity of 30 and 40 tons.

There is no experience of using tracked vehicles as mining haulage in the world [39, 40].

Robotic Mining Dump Trucks

The use of unmanned dump trucks in mining is no longer a prospect, it is our reality. A driver is replaced by a central controller. The absence of a driver's cab

allows you to significantly change the layout and ergonomics of the vehicle (Fig. 4). Mining robotic dump trucks can be used in remote controlled, semi-autonomous and autonomous modes.

Each of the autonomous dump trucks is equipped with controllers and systems of GPS, obstacle detection and wireless network system.

The mining holding SUEK, OJSC (Russia) already uses two robotic dump trucks BelAZ-7513R with a lifting capacity of 136 tons at the Abakansky open-pit mine in Khakassia.

In 2015, the Rio Tinto robotic fleet of the British Mining and Metallurgical Corporation at the Western Australia Iron Ore Mine amounted to 69 dump trucks [41].

More than 130 autonomous dump trucks Komatsu AHS (Autonomous Haulage System) and Caterpillar (Cat 793F. Cat 797F and Cat 789D with payload capacities of 227, 363 and 181 tons, respectively) are operated in seven quarries in three continents [41]. In 2018, Volvo Construction Equipment began using the HX2 autonomous dump trolley-trucks at the Vikan Cross quarry in Gothenburg, Sweden and the Volvo FH autonomous dump trucks to transport limestone from the Bronnoy Kalk AS quarry to the port [42].

As of March 2019, the series of robotic dump trucks includes the Cat 789D, Cat 793F. The Cat 797F with lifting capacities of 181, 227 and 363 tones, respectively. These vehicles independently respond to calls from the excavator, move to a desired place, transport rocks to an unloading point and provide all the telemetry needed to make maintenance solutions.

During work cycles, the robotic dump trucks can follow trajectories with an accuracy of several centimeters, which saves on the width of the carriageways, ledges and steep inclines, as well as on the number of turning points. It has been revealed that the autonomous freight haulage can increase productivity by 15-20 %, reduce fuel consumption

a *b*

Fig. 4. Robotic dump trucks *a*) Komatsu; b) Volvo

by 10-15 %, reduce tire wear by 5-15 %, reduce maintenance costs by nearly 8 % and increase vehicle utilization by 10-20 % with a good driving practice [41, 43-45]. Intelligent systems are able to replace drivers on the serpentines of mining in difficult situations, especially after rain and snow [43, 45]. Such machines can work 24/7, eliminate the human factor, reduce the number of accidents and increase operational safety [41, 43–45].

Robotic dump trucks are more stable, predictable and safer vehicles. Complex solutions will be of great interest, e.g. centralized systems that allow working with an autonomous fleet and other systems. Therefore, these kinds of technologies are proven to be the most developing and promising ones.

Conclusions

Mining haulage has historically come a long way of progress. The results of using the first models of new mining equipment, such as trolley-trucks, robotic and gas turbine dump trucks, the use of gas engine fuel, artificial intelligence systems, have proven to offer significant cost reductions for transporting rock mass by saving diesel fuel, reducing distances, improving route accuracy and increasing environmental safety.

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