Mining of Mineral Deposits
Volume 19 (2025), Issue 2, 47-55

MMD
JOURNAL / MINING.IN.UA

https://doi.org/10.33271/mining19.02.047

Assessing the performance efficiency of haul trucks and diesel-trolley trucks when changing their technological states and parameters of traffic routes

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Abstract

Purpose. The research aims to assess the efficiency (performance) of haul trucks and diesel-trolley trucks, taking into account their technological states and parameters of traffic routes.

Methods. The study of the technological states of dump trucks and diesel-trolley trucks was conducted using the mathematical apparatus of Markov random processes and the theory of road transportation with adaptation to quarry transport.

Findings. The probabilities of vehicles being in each of the 12 (16) states and the performance of a haul truck and a diesel-trolley truck with a carrying capacity of 130 tons at the length of traffic routes from 1 to 5 km with the specific part of the trolley section from 30 to 70% have been found. The nonlinearity of the process of decreasing/increasing the relative importance of a particular component of the vehicle's operating cycle has been determined, depending on the change in the route length and the share of the trolley section. Given the same technical service time for haul trucks and diesel-trolley trucks, the difference in movement velocity results in a change in travel time, which allows diesel-trolley trucks to perform up to 40% more transport work. On a 3 km route, which is the average transportation length in the Kryvyi Rih quarries, the performance of quarry transport increases from 13 to 36%, depending on the increase in the share of the trolley section from 30 to 70%.

Originality. For the first time, a mathematical model of the probabilities of a diesel-trolley truck being in different technological states has been developed, which is used to determine the corresponding probabilities when changing the length of traffic routes and the share of the trolley section within them.

Practical implications. The patterns revealed make it possible to determine the predicted reliability of operation, the probability of vehicles being in each of the states, and the productivity of using diesel-trolley trucks compared to dump trucks of similar carrying capacity under specified operating conditions. The use of diesel-trolley trucks can increase the performance of quarry road transport, with the best results observed on routes of maximum length with the longest trolley section.

Keywords: *quarry, transport, dump truck, diesel-trolley truck, performance, operating conditions*

1. Introduction

The electrification of haul trucks is considered a promising direction for improving technological road transport in large quarries in terms of improving its operating efficiency and reducing environmental impact [1]-[3]. Depending on the method of electrification, its implementation requires the modernization of existing working ramps in the quarry, adaptation of technological routes, provision of additional energy infrastructure and a change in approaches to servicing the vehicles [4]-[8]. In this case, before solving these tasks, it becomes necessary to take into account both the mining-technical and road-transport conditions of operation of haul trucks, as well as being of dump trucks in the appropriate technological state.

An analysis of recent research and publications on the prospects for improving technological road transport in large quarries shows that one of the directions is the introduction of diesel-trolley trucks [9]-[11]. The world's leading manufacturers of haul trucks and electrical machines for transportation [12], [13] also show interest in this direction. The fact is that the use of modern dual-flow transmissions in vehicles equipped with a diesel engine provides the necessary traction force and infinitely-variable movement velocity control when the diesel engine is running at a constant crankshaft rate [14], [15]. This, in turn, guarantees minimal fuel consumption and, as a result, reduced exhaust gas emissions into the atmosphere [16], [17]. In the scientific and technical literature, many schemes of hydromechanical continuously variable transmissions have been published, and different schemes are proposed for different vehicles.

Recently, there has been a growing interest in using diesel-trolley trucks in quarries. Mining companies in Panama, Aus-

Received: 16 September 2024. Accepted: 17 April 2025. Available online: 30 June 2025

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

tria and Canada implement or have implemented diesel-trolley systems for mining. At the world's leading mining exhibitions, more and more exhibits are presented, dedicated to diesel-trolley trucks [13]. Additionally, strategic management in the transport and logistics sectors is increasingly focused on sustainable and flexible business models that can accommodate innovations like electrified transport systems [18].

Siemens Company is currently the largest company engaged in manufacturing and implementation of traction electric drives for mining machines and complexes since 1976, and diesel-trolley systems – since 1981. The number of electrified equipment produced by the company for mining and other industries exceeds 900 off-road and 16 thousand on-road vehicles, respectively. Siemens offers technology solutions to improve the efficiency and environmental friendliness of quarry road transport: trolley trucks with electromechanical transmission, traction batteries with electromechanical transmission, fuel cells in combination with traction batteries, trolley trucks with on-board battery [19].

According to the company, the highest efficiency of energy transfer from its source to the driving wheels of the vehicle is achieved when operating a trolley truck with traction batteries. The company's representatives also claim that the trolley system of a fully electrified dump truck allows for more efficient use of the power of traction electric motors compared to other technological solutions, which provides the possibility of increasing the dump truck movement velocity by up to 80%, especially on longitudinal slopes of routes up to 10% [19]. The transition to alternative fuel technologies in transport, such as hydrogen and electrified systems, is closely linked to broader decarbonization goals and sustainable development strategies in high-emission sectors [20]-[22]. The dump truck velocity increases due to the ability of the trolley system to provide more power compared to existing diesel engines operating with two traction electric motors (electric motor-wheels), which is confirmed by scientific research [23], [24]. Increasing the velocity of a diesel-trolley truck in the operating mode helps to shorten the transport cycle, increase the performance of the dump truck or reduce the number of vehicles required to ensure a given production volume.

In 2020, Caterpillar Company tested the CAT-795F AC diesel-trolley trucks with a carrying capacity of 313 tons at the Aitik copper quarry of the Boliden Company (Boliden Aitik) in northern Sweden with a 700 m long trolley section with a 10% slope of the hard-surfaced track. The results of the experiment proved that the use of the trolley system allows to increase the performance of the dump truck by increasing its technical movement velocity to 28 km/h, which is 2 times higher than the movement velocity of the diesel engine alone [13].

As of mid-2024, six Liebherr T236 haul trucks with a carrying capacity of 100 tons, equipped with a trolley system, are operating at the VA Erzberg iron-ore quarry in Austria. The contract for the development and implementation of this system was signed between Elberg and Liebherr in 2019, and the first tests of the system on a 500-metre section of roads with a trolley line were successfully carried out in 2020 [25].

An example of the wider implementation of trolley systems in quarry road transport is the case of ordering from the Liebherr manufacturer by the company First Quantum Minerals 11 diesel-trolley trucks based on Liebherr T284 dump trucks with a carrying capacity of 363 tons, of which three trucks are intended for operation at the Sentinel quarry (Zambia) and eight – at Cobre Panama in Panama [26]. Based on First Quantum Minerals' experience in implementing trolley systems, its Kansanshi copper-iron ore quarry in Zambia received its first haul truck from Hitachi Construction Machinery Co. Ltd. in January 2014 with dynamic battery charging that replaced a diesel engine and is charged through a pantograph from the trolley line [27].

The Copper Mountain quarry, located 20 km south of the city of Princeton (Canada), launched a project to use diesel-trolley trucks in 2022. A 1 km long trolley line was installed, the location of which is presented in [28], for transporting the rock mass by Komatsu 830E-5 diesel-trolley trucks.

Modern scientific research is aimed at studying the impact of mining-technical operating conditions on the performance indicators of haul trucks [29]-[31], including energy consumption during transportation [32], [33]. In [34], a comparative analysis of the performance of two types of haul trucks was performed, taking into account the availability factor and the failure intensity function for specific operating conditions. The impact of these factors on the overall reliability of the vehicles was assessed. The study of haul truck failures was based on the use of distribution models that most closely matched the empirical data obtained during the reliability analysis, in particular the Weibull probability density function. To improve the operational efficiency of haul trucks, a variant of their operation when changing the type of road surface was proposed and tested.

In [35], the technical-operational states of haul trucks were studied as attributes that determine specific stages during the vehicle operation process. To assess the efficiency of haul truck operation, the average time indicators between failures and the average time to repair were used. A mathematical model of haul truck operation at different levels of service organization was developed [36].

The transport cycle performance indicators of haul trucks was studied taking into account the impact on them of driver behaviour [37], as well as road-transport and mining-technical conditions in the quarry [38]-[40]. The study of the influence of traffic route parameters on the performance indicators of diesel-trolley trucks is most fully disclosed in [41].

In general, the efficiency of using the trolley system for trucks [42], [43], including for haul trucks, has not been studied enough, and only a few examples are presented in open sources to address this issue [44], [45].

Using the trolley system model of haul trucks, the authors in [46] studied the transport cycle of haul trucks at one of the copper-ore quarries. The modeling results showed a 44% increase in uphill movement velocity and a 16% reduction in travel time when using diesel-trolley trucks. In [47], research and modeling of a trolley system with energy recovery and parallel catenary for ascent and descent is presented, when the energy released during the braking of dump trucks going down is transferred to the catenary, where it is used to power the ascending dump trucks or returned to the power grid for transportation to the descent. The authors of [48] conclude that, compared to dump trucks with only diesel and electric motor for wheels, cyclic-flow technology for transporting rock mass, trolley systems combined with a traction battery, diesel-trolley trucks are an intermediate solution that provides an average level of performance and operational availability. However, this group of researchers continues to focus on studying the energy efficient trolley trucks with traction battery [9], [10], the high efficiency of which is confirmed by the developments of Siemens Company, as noted above [19]. In [49], the issue of implementing trolley systems in quarry road transport is studied using simulation modelling and field research.

Thus, an analysis of the current experience of mining companies and machine-building enterprises engaged in the production of heavy-duty haul trucks shows that the implementation of diesel-trolley trucks based on haul trucks with electric-mechanical transmission with a carrying capacity of 100 tons or more is an effective solution for improving the operation of quarry road transport and increasing its performance. This solution is appropriate for iron-ore quarries in Ukraine, in particular the ultra-deep quarries in Kryvyi Rih, which are characterized by a longitudinal slope of tracks up to 10%.

At the same time, research on the electrification of haul trucks using trolley systems remains an unresolved issue. Despite the availability of studies analyzing the effectiveness of electrification of quarry road transport by switching to diesel-trolley trucks, the amount and scope of studies that would take into account the impact of the technical condition of diesel-trolley trucks and quarry traffic conditions on their transport cycle indicators and, accordingly, on the performance of such vehicles compared to dump trucks equipped with only electromechanical transmission, remains insufficient. Eliminating this problem will allow making more informed decisions on the introduction of electrification in quarry road transport.

Thus, the purpose of this research is to study the influence of the length of traffic routes with different shares of the trolley section on the performance indicators of haul trucks and diesel-trolley trucks, taking into account changes in the technological state of these vehicles, which will make it possible to explore the feasibility of implementing diesel-trolley trucks for transporting rock mass in quarries.

To achieve the purpose set, it is necessary to solve the following objectives:

1. For determined technological states of a haul truck and a diesel-trolley truck, develop a graph of transitions from one technological state to another.

2. Develop a mathematical model of the probabilities of being a haul truck and diesel-trolley truck in each of the technological states and apply it to determine the probabilities of the corresponding state occurrence at different lengths of traffic routes and the share of the trolley section within them.

3. Determine patterns of change in the performance indicators of a haul truck and a diesel-trolley truck depending on the length of traffic route at different parts of the trolley section, which can be used to assess the feasibility of operating diesel-trolley trucks based on haul trucks.

2. Methods

The technological states of haul trucks, as well as diesel-trolley trucks based on them, change over time, both in a random, unforeseen way and in a predictable way. For the mathematical description of transitions from one state to another, the mathematical apparatus of Markov random processes is used. If a haul truck has N states, then the complete characteristic of its functioning will be a square intensity matrix of order NXN, in this matrix $\lambda_{i,j} \neq 0$. The intensity matrix provides a way to describe the process of functioning of a haul truck using the differential equations of A.M. Kolmogorov in the case when the rate of transition from one state to another is sufficiently high. When setting the current task of determining the influence of traffic route parameters on the performance indicators of vehicles, it is assumed that a haul truck has 12 states, and the diesel-trolley truck has 16 states (Table 1). Therefore, the complete characteristic of their functioning will be square intensity matrices of the order 12×12 and 16×16, in this matrix $\lambda_{i,j} \neq 0$.

The difference in the number of states for a haul truck and a diesel-trolley truck is due to the fact that the states of movement of loaded and unloaded vehicle are divided from one for a haul truck (t_4 and t_7 of the loaded and unloaded vehicle, respectively) into three consecutive states for a diesel-trolley truck, according to the structure of the traffic route sections, namely the section without a trolley near the loading point, the section with a trolley and the section without a trolley at the unloading point.

Table 1. States of a haul truck (HT) and a diesel-trolley truck (DTT)

No.	Designation	Probability of transition	State name
1	t_1	P_1	Waiting for loading
2	t_2	P_2	Load maneuver
3	t_3	P_3	Loading
4	t_4	P_4	Motion in a loaded state (for HT)
5	$t_{4.1}$	$P_{4.1}$	Movement in a loaded state on a section without a trolley near the loading point
6	$t_{4.2}$	$P_{4.2}$	Movement in a loaded state on a section with a trolley
7	$t_{4.3}$	$P_{4.3}$	Movement in a loaded state on a section without a trolley near the unloading point
8	t_5	P_5	Unload maneuver
9	t_6	P_6	Unloading (the time of lifting and lowering the platform)
10	t_7	P_7	Movement in the unloaded state in the opposite direction (for HT)
11	$t_{7.1}$	$P_{7.1}$	Movement in the unloaded state on a section without a trolley near the unloading point
12	$t_{7.2}$	$P_{7.2}$	Movement in the unloaded state on a section with or without a trolley, depending on the adopted scheme of movement of diesel-trolley trucks
13	$t_{7.3}$	$P_{7.3}$	Movement in the unloaded state on a section without a trolley near the loading point
14	t_8	P_8	Changing operators and performing shift-based technical servicing
15	t_9	P_9	Movement from the unloading point to the car park
16	t_{10}	P_{10}	Movement from the car park to the loading point
17	t_{11}	P_{11}	Being in a state of servicing
18	t_{12}	P_{12}	Being in a state of current repair

for HT and DTT; for HT only; for DTT only

That is, for movement with a load $t_4 = t_{4.1} + t_{4.2} + t_{4.3}$ and for movement without a load $t_7 = t_{7.1} + t_{7.2} + t_{7.3}$ for a haul truck and a diesel-trolley truck, respectively, according to the equations. The division is caused by the difference in the equipment used by the vehicles (connecting / disconnecting trolley equipment and an internal combustion engine operation with different power with cylinders connected/disconnected to save fuel consumption) when moving on certain sections of the route, which accordingly affects the possibility of changing the state. It is accepted that external factors, such as the road surface condition, weather and mining-technical conditions, affect the haul truck and diesel-trolley truck in the same way under the same conditions and can be ignored.

The number of state indicators and their characteristics may vary depending on the accepted system of servicing and repairing vehicles of a particular haul truck manufacturer. For example, when determining the reliability of truck operation, the states "Under servicing" and "Under repairing" can be disintegrated into several states [12].

The known structure of transitions from one state to another gives an opportunity to develop a graph of states of a haul truck as an integral system that includes its constituent functional elements and transitions between them (Fig. 1).

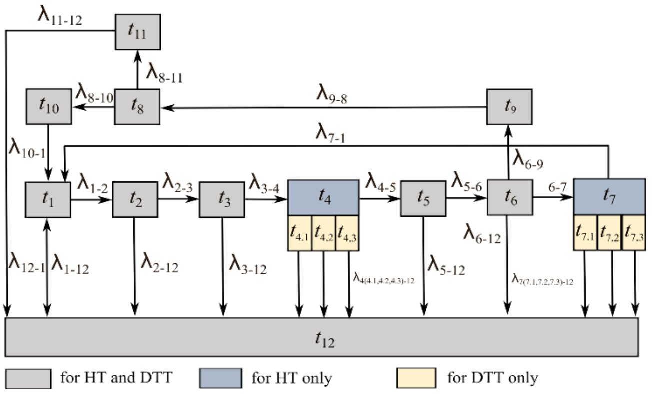

Figure 1. Graph of states for a haul truck and a diesel-trolley truck: t_i – state indication; λ_{ij} – intensity of transitions from one state to another (used in Markov processes)

Thus, the system of equations in which the probabilities $P_i(t)$ of a haul truck being in one of the states are searched for will have one form for ordinary haul trucks and a slightly different form for a diesel-trolley truck. In the first case, the movement of a loaded/unloaded vehicle is represented by one state t_4/t_7, which for a diesel-trolley truck is further divided into three more states $t_{4.1}/t_{7.1}$, $t_{4.2}/t_{7.2}$, $t_{4.3}/t_{7.3}$, and a system of 12 equations with 12 unknowns turns into into a system of 16 equations with 16 unknowns.

$$\begin{cases}
\frac{dP_1(t)}{dt} = -(\lambda_{1-2} + \lambda_{1-12}) \cdot P_1(t) + \lambda_{7-1} \cdot P_7(t) + \lambda_{10-1} \cdot P_{10}(t) + \lambda_{12-1} \cdot P_{12}(t) \\
\frac{dP_2(t)}{dt} = -(\lambda_{2-3} + \lambda_{2-12}) \cdot P_2(t) + \lambda_{1-2} \cdot P_1(t) \\
\frac{dP_3(t)}{dt} = -(\lambda_{3-4} + \lambda_{3-12}) \cdot P_3(t) + \lambda_{2-3} \cdot P_2(t) \\
\frac{dP_4(t)}{dt} = -(\lambda_{4-5} + \lambda_{4-12}) \cdot P_4(t) + \lambda_{3-4} \cdot P_3(t) \\
\frac{dP_5(t)}{dt} = -(\lambda_{5-6} + \lambda_{5-12}) \cdot P_5(t) + \lambda_{4-5} \cdot P_4(t) \\
\frac{dP_6(t)}{dt} = -(\lambda_{6-7} + \lambda_{6-12} + \lambda_{6-9}) \cdot P_6(t) + \lambda_{5-6} \cdot P_5(t) \\
\frac{dP_7(t)}{dt} = -(\lambda_{7-1} + \lambda_{7-12}) \cdot P_7(t) + \lambda_{6-7} \cdot P_6(t) \\
\frac{dP_8(t)}{dt} = -(\lambda_{8-10} + \lambda_{8-11}) \cdot P_8(t) + \lambda_{9-8} \cdot P_9(t) \\
\frac{dP_9(t)}{dt} = -\lambda_{9-8} \cdot P_9(t) + \lambda_{6-8} \cdot P_6(t) \\
\frac{dP_{10}(t)}{dt} = -\lambda_{10-1} \cdot P_{10}(t) + \lambda_{8-10} \cdot P_8(t) \\
\frac{dP_{11}(t)}{dt} = -\lambda_{11-12} \cdot P_{11}(t) + \lambda_{8-11} \cdot P_8(t) \\
\frac{dP_{12}(t)}{dt} = -\lambda_{12-11} \cdot P_{12}(t) + \lambda_{1-12} \cdot P_1(t) + \lambda_{2-12} \cdot P_2(t) + \lambda_{3-12} \cdot P_3(t) + \lambda_{4-12} \cdot P_4(t) + \\
+\lambda_{5-12} \cdot P_5(t) + \lambda_{6-12} \cdot P_6(t) + \lambda_{7-12} \cdot P_7(t),
\end{cases} \tag{1}$$

where:

$P_i = P_i(t)$ – probability of haul trucks being in each of the states.

$$\begin{cases}
\frac{dP_1(t)}{dt} = -(\lambda_{1-2}+\lambda_{1-12})\cdot P_1(t)+\lambda_{7.3-1}\cdot P_{7.3}(t)+\lambda_{10-1}\cdot P_{10}(t)+\lambda_{12-1}\cdot P_{12}(t) \\
\frac{dP_2(t)}{dt} = -(\lambda_{2-3}+\lambda_{2-12})\cdot P_2(t)+\lambda_{1-2}\cdot P_1(t) \\
\frac{dP_3(t)}{dt} = -(\lambda_{3-4.1}+\lambda_{3-12})\cdot P_3(t)+\lambda_{2-3}\cdot P_2(t) \\
\frac{dP_{4.1}(t)}{dt} = -(\lambda_{4.1-4.2}+\lambda_{4.1-12})\cdot P_{4.1}(t)+\lambda_{3-4.1}\cdot P_3(t) \\
\frac{dP_{4.2}(t)}{dt} = -(\lambda_{4.2-4.3}+\lambda_{4.2-12})\cdot P_{4.2}(t)+\lambda_{4.1-4.2}\cdot P_{4.1}(t) \\
\frac{dP_{4.3}(t)}{dt} = -(\lambda_{4.3-5}+\lambda_{4.3-12})\cdot P_{4.3}(t)+\lambda_{4.2-4.3}\cdot P_{4.2}(t) \\
\frac{dP_5(t)}{dt} = -(\lambda_{5-6}+\lambda_{5-12})\cdot P_5(t)+\lambda_{4.3-5}\cdot P_{4.3}(t) \\
\frac{dP_6(t)}{dt} = -(\lambda_{6-7.1}+\lambda_{6-12}+\lambda_{6-9})\cdot P_6(t)+\lambda_{5-6}\cdot P_5(t) \\
\frac{dP_{7.1}(t)}{dt} = -(\lambda_{7.1-7.2}+\lambda_{7.1-12})\cdot P_{7.1}(t)+\lambda_{6-7.1}\cdot P_6(t) \\
\frac{dP_{7.2}(t)}{dt} = -(\lambda_{7.1-7.3}+\lambda_{7-12})\cdot P_{7.2}(t)+\lambda_{7.1-7.2}\cdot P_{7.1}(t) \\
\frac{dP_{7.3}(t)}{dt} = -(\lambda_{7.3-1}+\lambda_{7-12})\cdot P_{7.3}(t)+\lambda_{7.2-7.3}\cdot P_{7.2}(t) \\
\frac{dP_8(t)}{dt} = -(\lambda_{8-10}+\lambda_{8-11})\cdot P_8(t)+\lambda_{9-8}\cdot P_9(t) \\
\frac{dP_9(t)}{dt} = -\lambda_{9-8}\cdot P_9(t)+\lambda_{6-9}\cdot P_6(t) \\
\frac{dP_{10}(t)}{dt} = -\lambda_{10-1}\cdot P_{10}(t)+\lambda_{8-10}\cdot P_8(t) \\
\frac{dP_{11}(t)}{dt} = -\lambda_{11-12}\cdot P_{11}(t)+\lambda_{8-11}\cdot P_8(t) \\
\frac{dP_{12}(t)}{dt} = -\lambda_{12-1}\cdot P_{12}(t)+\lambda_{1-12}\cdot P_1(t)+\lambda_{2-12}\cdot P_2(t)+\lambda_{3-12}\cdot P_3(t)+\lambda_{4-12}\cdot P_{4.1}(t)+\lambda_{4.2-12}\cdot P_{4.3}(t)+ \\
+\lambda_{5-12}\cdot P_5(t)+\lambda_{6-12}\cdot P_6(t)+\lambda_{7.1-12}\cdot P_{7.1}(t)+\lambda_{7.2-12}\cdot P_{7.2}(t)+\lambda_{7.3-12}\cdot P_{7.3}(t),
\end{cases} \tag{2}$$

where:

$P_i = P_i(t)$ – probability of diesel-trolley trucks being in each of the states.

At the initial point in time, it is assumed that the haul truck or diesel-trolley truck is parked:

$$P_0(t=0)=1\,;\; P_1(t=0)=0\,. \tag{3}$$

In this case, the condition of completeness of the system of technological states of the haul truck and diesel-trolley truck must also be met:

$$\sum P_i(t)=1\,. \tag{4}$$

Equations and initial conditions define the Cauchy problem. To solve this problem, it is necessary to find a general solution to the system of differential equations, and then, according to the initial conditions, to determine a partial solution.

An analysis of haul truck traffic routes at Ukrainian iron-ore mines showed that the length of the routes varies from 1 to 5 km, with an average value of 3 km. Therefore, studies have been conducted to determine the change in vehicle performance indicators specifically on routes of 1, 2, 3, 4, 5 km long, with determining mathematical patterns of parameter change depending on the length of the route (five values are the minimum number of points to ensure the reliability of the mathematical determination of the desired pattern). It is not possible to install a trolley within the boundaries of the mining block, at the unloading point, so the trolley section does not cover 100% of the traffic route, but only part of it. In this research, it is assumed that the trolley section is from 30 to 70% of the total length of the rock mass transportation. Less than 30% is considered inappropriate, and more than 70% is practically unattainable in real mining conditions, but on a 5 km route, 30% of the trolley section is 1.5 km, which is quite realistic and can be implemented.

To model the functioning of a haul truck and a diesel-trolley truck, two simulation models have been developed according to the state graphs using the Anylogic simulation tool [50]. Setting up a model experiment: model time – hours from the start of vehicle operation, model stop time – 8760 hours, equal to the number of hours in a normal year, corresponding to the cycle of the technical service system for haul trucks and diesel-trolley trucks, route length 1, 2, 3, 4, 5 km, the share of the trolley section within the total length of the route is 30, 40, 50, 60, 70%. Modeling was conducted in parallel for the same operating conditions of a haul truck and a diesel-trolley truck, followed by comparing the results and determining the relative indicators.

The next step in the research was to determine, in absolute and relative terms, the dependences of the change in the transportation performance by haul trucks and diesel-trolley trucks on the length of the travel with a load, with different specific ratios of the length of the trolley part (degree of trolleying) for vehicles with a carrying capacity of 130 tons used for the transportation of iron ore and overburden at Ukrainian quarries in Kryvyi Rih and Horishni Plavni.

The research was performed on the basis of proven methods for determining the parameters of quarry road transport operation and the theory of road transportations with adaptation to quarry road transport, taking into account previously conducted research by the authors [41].

In total, 30 calculations have been made, 5 for haul trucks (one for each route) and 25 for diesel-trolley trucks, which corresponds to the search for all possible variants of traffic routes with different share of the trolley section, five calculations for a 1 km route with five different trolley sections and five for routes of other lengths.

3. Results and discussion

Analysis of the patterns of change in a haul truck being in each state with the length of routes of 1, 2, 3, 4, 5 km shows the nonlinearity of the process of decreasing/increasing the share of a particular component of the vehicle's operating cycle (Fig. 2). An increase in the length of the traffic route from 1 to 5 km leads to an increase in the share of movement in the loaded state from 0.41 to 0.56, by almost a third. Similarly, the share of movement in the unloaded state increases by almost a third from 0.14 to 0.19 (Fig. 2).

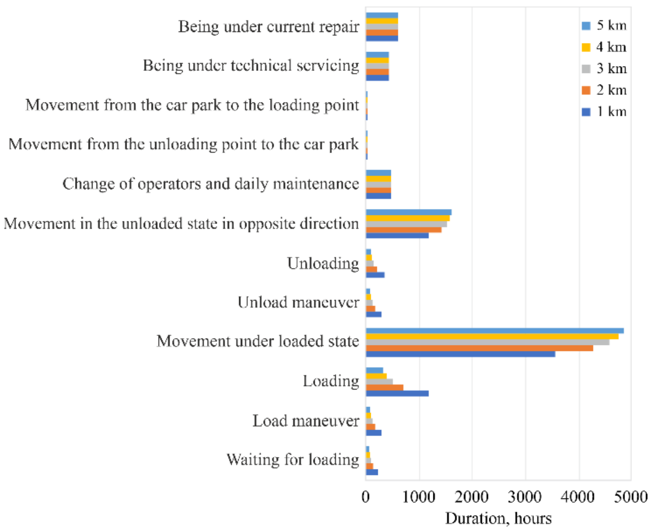

Figure 2. Comparison of the time a haul truck being in each state at different track lengths

At the same time, the share of the haul truck loading decreases from 0.14 to 0.04. Being under technical servicing and repair does not depend on the length of travel with the load, which is conditioned by the accepted system of technical service for haul trucks based on hours of operation, not on mileage (as for public vehicles).

Analysis of the patterns of change in a haul truck being in each state with the length of routes of 1, 2, 3, 4, 5 km shows the nonlinearity of the process of decreasing/increasing the share of a particular component of the vehicle's operating cycle (Fig. 3). The modeling performed to determine the indicators of the diesel-trolley truck being in each state at a route length of 1 km with a trolley section of 30% and 5 km with a trolley section of 70% (Fig. 3) shows that the share of vehicle travel time increases while the share of operations that are not directly related to the transport cycle decreases. The determined indicators are Change of operators and shift-based technical servicing, Movement from unloading point to parking, Movement from parking to loading point, being under technical servicing, Being under current repair.

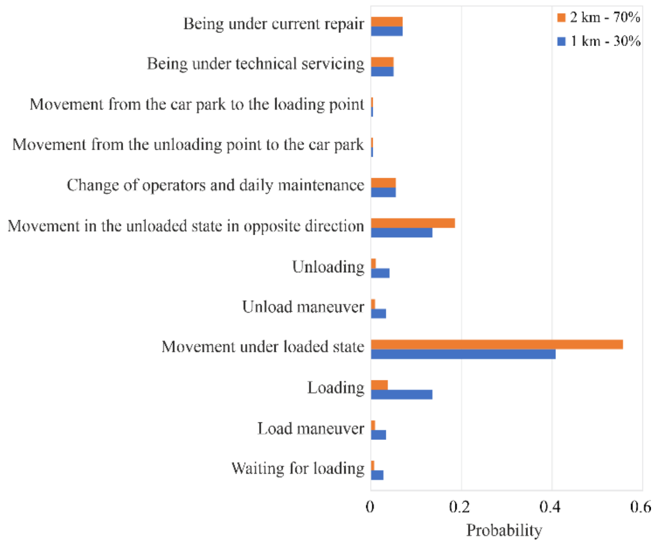

Figure 3. Probability of diesel-trolley truck being in a technological state at the route length: 1 km with 30% trolley section; 5 km with 70% trolley section (minimum and maximum values for diesel-trolley truck use, showing probability variation limits)

An analysis of the patterns of change in travel time with a load, without a load, and total travel time depending on the length of the traffic route shows that the longest travel time is for haul trucks, and the shortest for diesel-trolley trucks on routes with a 70% trolley section, which is quite logical. The total travel time is close to 6200-6500 hours, which is about 70% of the total annual time (Fig. 4).

With the same reliability of a haul truck and a diesel-trolley truck (time for performing technical servicing and repairs), due to the difference in the vehicle movement velocities, the travel time in the loaded and unloaded state changes, as well as one operating transport cycle. The number of travels with load changes accordingly with the same operating hours and the transport work performed.

In general, the absolute performance of trucks is determined as the weight of load transported over a certain period of time, with a fixed carrying capacity and utilization factor of carrying capacity (Fig. 5).

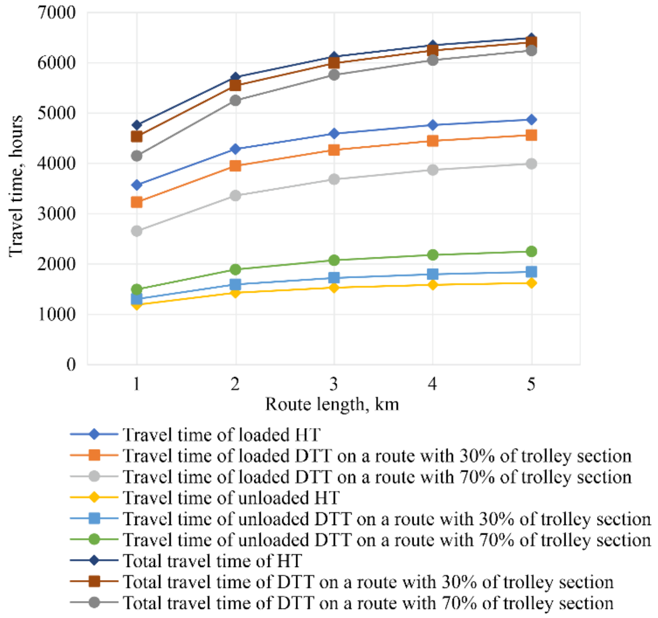

Figure 4. Patterns of change in travel time with a load, without a load, and total travel time depending on the length of the traffic route (in hours per year)

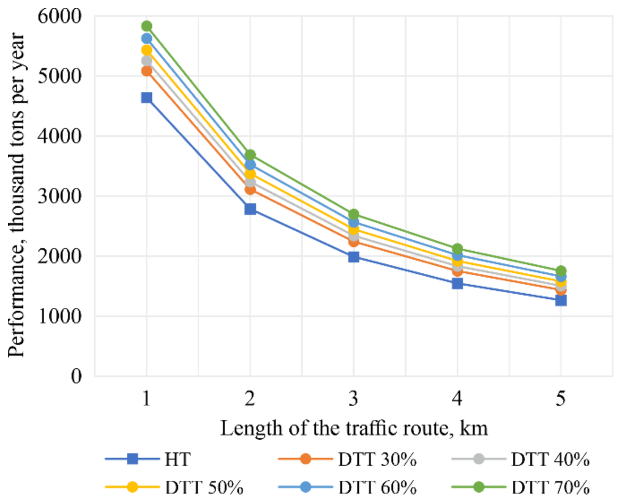

Figure 5. Patterns of changes in the absolute annual performance of haul trucks (HT) and diesel-trolley trucks (DTT) with the length of the route at different parts of the trolley section

The values of absolute annual performance (Fig. 5) are determined during the operation of haul trucks and diesel-trolley trucks on routes with different lengths. This performance was used as a basis for comparison with performances on routes with a trolley section. When calculating the specific performance, the numerator is the performance of a diesel-trolley truck on a route with a trolley section, and the denominator is the performance of a conventional haul truck with the same carrying capacity as the diesel-trolley truck.

There is a natural power-law (probability value of approximation $R^2 = 1.00$) pattern of decreasing haul truck performance with increasing length of load transport from 1 to 5 km. In this case, the larger the part of the trolley section, the higher the performance, which is caused by a higher movement velocity of a loaded diesel-trolley truck precisely along the trolley section.

The obtained performance value of haul trucks compared to those achieved in production are somewhat overestimated as a result of assuming maximum values of vehicle reliability indicators, ideal conditions for organizing the transportation process and operating the vehicles. In real conditions, on average, according to PJSC Inhulets Mining and Processing Plant, Northern Mining and Processing Plant (Northern GOK) and Southern Mining and Processing Plant (Southerm GOK) (based on data available to the authors), new 130-ton capacity haul trucks transport about 1.5 million tons per year over a distance of 2.5 km.

The obtained numerical values of specific performance (Fig. 6) are within the range of 4-10% increase in the performance of quarry road transport. These indicators are consistent with performance improvement data, which are guaranteed by manufacturers of trolley systems and diesel-trolley trucks [12], [14].

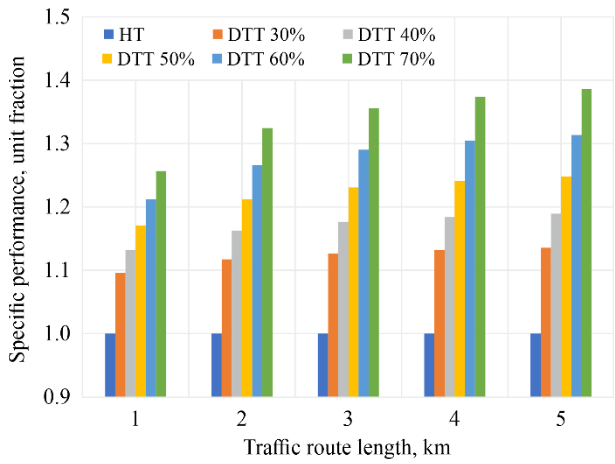

Figure 6. Patterns of change in specific performance depending on the route length at different parts of the trolley section

In contrast to existing studies, the ranges of increasing the performance of quarry road transport when using a trolley system have been determined, depending on the route parameters. Thus, increasing the movement velocity of vehicles along the trolley sections from 8 to 24 km/h provides an increase in performance by no more than 40% on a 5 km long route with a 3.5 km trolley section (70% of the total length of the route). On the shortest route of 1 km long with a 0.3 km trolley section, an increase in performance is 1.09 times. In general, on a 1 km long route, the maximum increase in relative performance is 25%. On a 3 km route, which corresponds to the average transportation length, performance increases from 13 to 36% with an increase in the trolley section from 30 to 70%. When the route length increases by more than 3 km, the further increase in specific performance practically stabilizes.

4. Conclusions

To describe the process of functioning of a diesel-trolley truck, given a graph of its transitions from one technological state to another, a mathematical model for the probability of a diesel-trolley truck being in each of the technological states, consisting of 16 equations with 16 unknowns, is used for the first time. With the same reliability of a haul truck and a diesel-trolley truck, when taking into account the time required for technical servicing and repair, the main difference in performance indicators is the movement velocity of these vehicles, which in turn influences the total time required to perform one working transport cycle. It has been determined that an increase in the share of trolley section of routes to 70% can reduce the total travel time of a haul truck from 4% (for a 1 km long route) to 13% (for a 5-kilometre route). It has been confirmed that the use of diesel-trolley trucks can increase the performance of quarry road technological transportations, but the best indicators will be on the routes of maximum length with the maximum trolley section length.

Using the identified patterns, it is possible to determine the performance of diesel-trolley trucks in other operating conditions when determining the feasibility of implementing diesel-trolley trucks in a quarry.

The directions of further research are related to the analysis of fuel efficiency and environmental friendliness of haul trucks with diesel engines with a carrying capacity of 90 to 220 tons, as well as similar dump trucks equipped with a trolley system under different conditions of rock mass transportation at different stages of operation in deep quarries.

Author contributions

Conceptualization: YM, VS; Data curation: VS, UK; Formal analysis: YM, VS, UK; Investigation: YM, IT; Methodology: YM, VS; Project administration: IT; Resources: UK, VS; Software: YM, VS, IT; Supervision: YM, IT; Validation: YM, IT; Visualization: VS, UK; Writing – original draft: YM, UK; Writing – review & editing: IT, VS. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Оцінка ефективності роботи кар'єрних автосамоскидів та дизель-тролейвозів при зміні їх технологічних станів і параметрів трас руху

Ю. Монастирський, І. Таран, У. Кокаєв, В. Сістук

Мета. Оцінка ефективності (продуктивності) роботи кар'єрних автосамоскидів та дизель-тролейвозів з урахуванням їх технологічних станів і параметрів трас руху.

Методика. Дослідження технологічних станів автосамоскидів та дизель-тролейвозів проведено із застосуванням математичного апарату Марківських випадкових процесів та теорії автомобільних перевезень з адаптацією до кар'єрного транспорту.

Результати. Встановлені ймовірності знаходження в кожному з 12 (16) станів та продуктивності кар'єрного автосамоскиду і дизель-тролейвозу вантажопідйомністю 130 т при довжині трас руху від 1 до 5 км та питомій частини тролейної ділянки від 30 до 70%. Встановлено нелінійність процесу зменшення/збільшення питомої ваги того чи іншого компоненту робочого циклу машини залежно від зміни довжини траси та питомої ваги тролейної дільниці. При однаковому часі на технічний сервіс кар'єрних автосамоскидів та дизель-тролейвозів внаслідок різниці у швидкостях руху змінюється час руху, що забезпечує виконання дизель-тролейвозами більшої транспортної роботи до 40%. На трасі довжиною 3 км, що є середньою довжиною перевезення на Криворізьких кар'єрах, продуктивність кар'єрного транспорту збільшується від 13 до 36% залежно від зростання частки тролейної ділянки з 30 до 70%.

Наукова новизна. Вперше розроблено математичну модель ймовірностей знаходження дизель-тролейвозу в різних технологічних станах, застосовану для визначення відповідних ймовірностей при зміні довжин трас руху та частуки в них тролейної ділянки.

Практична значимість. Встановлені закономірності дозволяють визначати прогнозну надійність роботи, ймовірність знаходження машин в кожному зі станів та продуктивність використання дизель-тролейвозів у порівнянні з автосамоскидами аналогічної вантажопідйомності в заданих умовах експлуатації. Використання дизель-тролейвоз може підвищити продуктивність кар'єрних автомобільних перевезень, причому найкращі результати спостерігаються на трасах максимальної довжини з найбільшою довжиною тролейної ділянки.

Ключові слова: *кар'єр, транспорт, самоскид, дизель-тролейвоз, продуктивність, умови експлуатації*

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