Ensuring Energy Efficiency and Safety of the Cyclic Operation of the Mining Dump Truck

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Abstract. It's known that the use of the automobile vehicles in a quarry for transporting the rock mass is characterized by a cyclic nature and the ability to overcome the slopes of up to 8-12% along the road as well as curves with the radii of at least 20-24 m. However, the disadvantage of this way of transportation of quarry loads is relatively high costs [1]. One of the ways to reduce costs is to implement the software-based operation of the mining dump truck while ensuring energy efficiency and safety. This way implies following the route “mine face – concentrator” when driving with the rock mass and the route “concentrator – mine face” when driving without a cargo along the specified trajectory and at a given driving speed using the information management systems in a quarry and on the board of the mining dump truck controlled by the driver as well as in an unmanned version in case of autonomous driving. The article describes the method to optimize the function “way – speed” and as a result the way to optimize the control of the traction electric motors in a mining dump truck during cyclic movement along the specified trajectory with a fixed time to pass the route in order to ensure energy efficiency and safety when using the method of dynamic programming developed by Richard Bellman.

1 INTRODUCTION

The effective way to reduce the amount of power consumed on a cyclic route is to implement the energy-efficient program-based control of the traction electric motors along the mining dump truck route. Given the fact that the truck route (trajectory) is known in advance, it would be reasonable to build the traction motor control algorithm so as to make the law of motion of the dump truck optimal in terms of minimization of energy input as well as safe (in terms of controllability and stability, limited maximum speed along the route and in terms of braking behavior) while the driving time is set based on the way the quarry load transportation is organized.

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Thus, the objective comes down to finding the optimal process to move the dump truck from the initial point of the route to the end point given the limits imposed on phase coordinates and the time of driving. There are a variety of methods [2–9], to find a solution for the problem of optimization the way it is stated, one of which is the method of dynamic programming used in this work.

2 Results and Discussion

2.1. Analysis of the dump truck behavior when operated in a quarry

Generally, the driving process of a mining dump truck without a forced change of speed due to obstacles (in case of emergency situations) on the road can be represented by 4 stages for a total: hastening and/or maintaining speed where necessary, i.e. a smooth increase in speed up to the set value while limiting phase coordinates and control; coasting, that is, driving without transmitting power to the vehicle wheels; regenerative braking, i.e. braking by an electric motor operated in a generator mode to store the part of the vehicle driving kinetic energy in the on-board energy storage device; braking by a service braking system, i.e. braking using friction brakes to stop in a defined location or in the event of emergency situations (no energy is used during driving to reduce non-recoverable energy consumption).

The problem of determining the law of the energy-efficient control of the wheeled mining dump truck when driving along the known route should be defined as a problem of optimization: determining the rate of change of momentum from the path traveled $v(s)$ on the route when moving from a point with phase coordinates s_1 , $v_1 = 0$ to the point s_2 , $v_2 = 0$ during the time $T = t_2 - t_1$ while minimizing the energy consumption per movement determined by the objective function:

$$J = \int_{t_1}^{t_2} (N_p - N_r) dt = \int_{t_1}^{t_2} N_{el} dt \Rightarrow \min, \quad (1)$$

where: N_p – is the the electrical power consumed from the on-board energy storage device and/or from the generating unit while accelerating (maintaining) the speed; N_r – is the electrical power returned to the on-board energy storage device during regenerative braking; N_{el} – is the total electrical power supplied by the on-board energy storage device and/or generator unit during acceleration or compensated for during braking.

The discrete variant of dynamic programming method used for optimization of the dump truck movement control laws is based on the principle of optimality formulated by Richard Bellman [3]: an optimal management strategy has the property that, whatever the initial state and decision at the outset, subsequent decisions should shape an optimal management strategy in relation to the state obtained from the first decision [8, 9].

2.2. Mathematics model of the mining dump truck dynamics

To solve the specified problem of optimization is necessary to describe the dump truck movement in equation connecting the actual state of the system and the control action with the subsequent state. To do this, we will use the equation of motion of the dump truck as a solid body without the longitudinal sliding (slipping) of wheels and the assumption that there is a “point” contact with the bearing surface (with a relatively small area of contact) expressed in terms of traveled path s и speed v [9, 10, 11]:

$$\begin{aligned} (m\delta + J_z k^2(s))v dv/ds + J_z v^2 k(s) dk(s)/ds = \\ = M_k/r_{k0} - mg(f^* \cos(\alpha) + \sin(\alpha)) - c_x F_{fr} \rho v^2/2, \end{aligned} \quad (2)$$

where: m – is the vehicle weight; δ – is the rotational inertia coefficient [12]; J_z – is the moment of inertia of the vehicle around the vertical axis passing through the center of the mass; $k(s)$ – is the trajectory curvature; v – is the vehicle speed; M_k – is the total torque transmitted to the vehicle's drive wheels; r_{k0} – is free rolling radius; g – is the gravitational acceleration ($9,81 \text{ m/c}^2$); f^* – is the reduced coefficient of rolling resistance with consideration of driving and drift speed; α – is the climbing/slope angle; c_x – is the aerodynamic drag factor; F_{fr} – is the vehicle forward-facing area; ρ – is the air density.

The dependence of the rolling resistance coefficient on driving and drift speed can be considered by using the following formula: [9, 12, 13, 14, 15]:

$$f^* = f_{gr}(1 + k_v v^2) + v^4 k^2(s) / (g^2 \zeta_y), \quad (3)$$

where: f_{gr} – is the rolling resistance coefficient at a low driving speed without a drift; k_v – is the speed loss factor; ζ_y – is the cornering coefficient.

The control system should ensure the design speed of the dump truck by means of traction/braking torque generated by traction electric motors and transmitted to the wheels through the mechanical powertrain part taking into account the losses by actuation of the additional equipment, then:

$$M_{teg} = M_k / n_{teg} u_{tp} (\eta_{tr} k_{cN})^{sign(M_k)}, \quad (4)$$

where: M_{teg} – is a torque generated by traction electric motors (TEM); k_{cN} – is the free capacity coefficient.

The power consumed by the dump truck driving, at the same time, should be calculated using the efficiency factor of the traction electric motor and the converter:

$$N_{el} = n_{teg} M_{teg} \omega_{teg} / (\eta_{con} \eta_{teg})^{sign(M_k \omega_k)}, \quad (5)$$

where: ω_{teg} – is the arithmetic mean of the traction electric motor rotor speed ($\omega_{teg} = v \cdot u_{tp}/r_{k0}$); η_{con} – is the converter efficiency; η_{teg} – is the electric motor efficiency.

This is how we obtained the equation of relationship between the current dump truck state $v(s)$ and control $M_{трэд}$ and the next state (2), required for optimization, as well as the dependence for determining the electric power required for transition from the current dump truck state to the next state.

2.3. Mathematical description of the route

With the help of GPS receiver and Navitel Navigator 9.12 software, GPS tracks were obtained, which are arrays of coordinates of points in space and time. The records form a curved line showing on the map the trajectory of the real movement of the dump truck on the route "face - concentrator" taking into account differences in altitude. The information about the recording time of points allows you to determine the speed of the dump truck on the route at a given time and in any road section.

The plane projection of the route recorded with GPS was obtained using the coordinate system of Universal Transverse Mercator Projection (UTM) (Fig. 1).

To synthesize the optimal control law for traction electric motors, we need to present the route as an extended implementation of the trajectory curvature and the climbing/slope angle of the traveled path (Fig. 2).

To make a comparative assessment of the electric power consumed during driving according to the optimal law with the energy consumed during driving according to the implementation recorded with the help of GPS, we found the dependence of the dump truck driving speed on the distance travelled when driving along the route.

The driving time of the dump truck along the considered route between the face and the concentrator was 1295 s.

Fig. 1. Plane projection of the dump truck motion path and variation of the vertical coordinate of the reference surface when moving along the trajectory.

When considering variation of driving parameters when moving in a “straight direction”, i.e. when driving from the point with 0 path coordinate (face) to the end point (concentrator) and in a “reverse direction”, it means from the point with a path coordinate corresponding to the length of the trajectory to the point with zero coordinate, we will get two route cases for the study: the vehicle is driving with the maximum weight (full load) from the face to the concentrator and the vehicle is driving with the minimum weight (empty) from the concentrator to the face.

Fig. 2. Dependencies of the path curvature and angle of slope of the reference surface on the traveled path when traveling along the route.

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It is obvious that the lower dump truck weight during empty running will potentially provide a higher vehicle driving speed. However, the time limits for driving from the face to the concentrator and from the concentrator to the face are equal to prevent tailbacks in front of loading and unloading points.

2.4. Method for the synthesis of law of the energy-efficient dump truck driving

The obtained equation of the dump truck state, dependence for calculating the functional as well as route description in a format required to conduct the study allow us to proceed directly to the application of the method of dynamic programming.

At the first stage we need to define the phase space, i.e. phase space of the dump truck states, where it can physically be, provided it fulfills the boundary conditions.

To do this, we need to integrate the obtained equation of motion (2) having fixed the initial boundary conditions ($s_1, v_1 = 0$) and provided transmission of traction torque to the drive wheels according to the external characteristics of the electric motor when moving from the initial state to the end state. It means, we have to define the maximum driving speed on the route limited by traction capabilities of the dump truck v_{dr} .

Apart from restrictions imposed by mechanical properties of the electric motors, when performing integration, it is necessary to take into account the limited driving speed of the vehicle related to the rules of operation in a quarry for the dump trucks (maximum driving speed is limited by the value of $v_{max} = 42 \text{ kph}$) and the traffic safety rules. Let us assume that the value of lateral accelerations of the safe driving is $a_{y \max} = 0,07g$. Then, proceeding from the value $a_{y \max}$, the limiting driving speed of the dump truck in the route i -point can be found as follows:

$$v_{ay \ i} = \sqrt{a_{y \max} / k_i}, \quad (6)$$

where: $v_{ay \ i}$ – is the maximum driving speed of the dump truck in the route i -point based on the limitation imposed to the lateral acceleration.

After that, we need to find the solution of the equation of motion (2) having fixed the end boundary conditions ($s_2, v_2 = 0$) and provided the transmission of braking torque to driving wheels according the external mechanical characteristics of the electric motor (in a generator mode) when moving from the end state to the initial one. In other words, we have to define the maximum driving speed limited by braking capabilities of the dump truck (without emergency application of friction brakes) v_{br} .

So, we obtained curves limiting the phase space in which the dump truck can be located, provided that the control traction/brake torque (limited by the external mechanical characteristics of the electric machine in traction/generator mode) will be sufficient to ensure the specified boundary conditions. The final value of speed limiting the phase space at the top at each point of the route is determined as $v_i = \min(v_{dr \ i}, v_{br \ i})$.

The bottom part of the phase space is limited by the zero speed line. The schematic representation of the obtained phase space is shown in.

The next step is to sample the obtained space, i.e. to split the phase surface into a lattice of the considered states. Let's split the considered path section into N points, and the certain speed limits into L points. Since the range of the allowed speeds can vary for each point of the considered path, the number of speed partition points in the considered path point will be L_i , where i is the number of points on the path in the examined route (Fig. 3).

The duration of the calculation and the accuracy of the resulting control law depend directly on the sampling (partition) rate. The size of the step should be varied depending on the length of the examined route: the greater the length of the route, the larger step can be chosen, thus obtaining a satisfactory result [9, 10].

It is advisable that the chosen integration step of the equation of motion for obtaining the speed limitation lines which form the phase space is equal to the sampling rate (the smaller step won't provide the increase of calculation accuracy).

During the next stage you need to create the Bellman function. The electric power consumed by the dump truck when driving along the route is chosen as a functional for the considered system. In this case, the value of Bellman's function in each calculation point of the phase space should represent the minimal value of the electric power that should be consumed to move the dump truck from the considered state to the end state taking into account the restriction imposed on the controlling action (the torque value should be within the limits of the mechanical characteristics).

In addition to design restrictions, when calculating the Bellman's function, it is advisable to take into account the limit value of the longitudinal accelerations $a_{x\max} = 0,1g$ [16]. Such a restriction is used to provide safety when several dump trucks are driving along the one route in a quarry, also when controlled by the operators. Thus, the Bellman's function in the considered case will be represented as follows: (Fig. 3):

$$Z_{N-i,k} = \min_{\substack{|M_{teg}| < M_{teg}^{max}(v_{av}) \\ |v_{av}\Delta v/\Delta s| < a_{x\max}}} \left\{ \frac{N_{el}(v_{av}, \Delta v, s_{av}, \Delta s) + \lambda}{v_{av}} \Delta s + Z_{N-i+1,j} \right\} \quad (7)$$

$$\begin{aligned} v_{av} &= (v_{N-i+1,j} + v_{N-i,k})/2; \quad \Delta v = v_{N-i+1,j} - v_{N-i,k}; \\ s_{av} &= (s_{N-i+1} + s_{N-i})/2; \quad \Delta s = s_{N-i+1} - s_{N-i}, \end{aligned} \quad (8)$$

where: $Z(s, v)$ – is the value of Bellman's function in the phase space point with the length of the traveled path s and speed v ; N – is the number of partition points of the examined route on the way; i – is the number of the considered point in the examined route $k \in [1 \dots N]$; k – is the number of the considered point in the array of allowed speeds for $(N-i)$ point along the route $k \in [1 \dots L_{N-i}]$; j – is the number of the considered point in the array of allowed speeds for $(N-i+1)$ point along the route $j \in [1 \dots L_{N-i+1}]$; λ – is the Lagrange undetermined multiplier; Δv – is the speed variation when the dump truck is transiting from the state $s_{N-i}, v_{N-i,k}$ to the state $s_{N-i+1}, v_{N-i+1,j}$; Δs – is the change of traveled path during dump truck transition from the state s_{N-i} to the state s_{N-i+1} ; v_{av} – is the average dump truck speed when transiting from the state $s_{N-i}, v_{N-i,k}$ to the state $s_{N-i+1}, v_{N-i+1,j}$; s_{av} – is the average value of the traveled path during dump truck transition from the state s_{N-i} to the state s_{N-i+1} ; $N_{el}(v_{av}, \Delta v, s_{av}, \Delta s) \cdot \Delta s / v_{av}$ – is the value of power consumed by dump truck transition from the state $s_{N-i}, v_{N-i,k}$ to the state $s_{N-i+1}, v_{N-i+1,j}$.

This means that the value of Bellman's function in the point with phase coordinates $N-i, k$ is the minimal value of the electric power required for transition of the dump truck from the state with phase coordinates $N-i, k$ to the state $N-i+1, j$ and values of Bellman's function in the point with phase coordinates $N-i+1, j$ (minimum amount of power which should be consumed for transition of the dump truck from the state with coordinates $N-i+1, j$ to the end state) provided that the control M_{teg} applied to the system as well as the longitudinal acceleration are within the tolerance range (Fig. 3).

The value of the consumed electric power $N_{el}(v_{av}, \Delta v, s_{av}, \Delta s)$, depending on the considered states $N-i, k$ и $N-i+1, j$ is determined using the equation of the dump truck dynamics (2) as well as formulas (4) and (5).

Consequently, when calculating the value of the Bellman's function (9) in each phase space point in case of moving from the end state to the initial state, we will get a two-dimensional array of the minimal power values to be consumed for transition of the dump truck from the considered phase space point to the end one. The calculations are performed exactly in the sequence from the end state to the initial one because the value of $Z(s, v)$ function in the end point of the route is the value of power to be consumed for transition of the dump truck from the end point of the route to the end point, i.e. 0.

The next step is the synthesis of the optimal phase trajectory and the law of control of the traction electric motor. Let us write the equation of state. Since the position of dump truck on the phase surface depends on the previous state and the value of the control action during this step $M_{\text{тэд}}$:

$$Z(s_{i+1}, v_{i+1,j}) = Z(s_i, v'_i) + (N_{el}(s_i, v'_i, M_{\text{тег}}) + \lambda) \Delta s / v_{av};$$

$$v_{av} = (v_{i+1,j} + v'_i) / 2; \quad \Delta s = s_{i+1} - s_i,$$
(9)

where: v'_i – is the value of optimal speed for s_i value of the traveled path.

Now, when moving from the initial state to the end one (as for the value $i = 1$ the value $v'_1 = 0$ is known) and when calculating the equation of state (9) in relation to $v_{i+1,j}$, we obtain the optimal phase trajectory $v'(s)$ on the considered route as well as the value of the required electric motor torque $M_{\text{тег}}(s)$, ensuring the dump truck driving along the obtained phase trajectory (Fig. 3).

$$J = \int_{t_1}^{t_2} N_{el} dt = \int_{s_1}^{s_2} \frac{N_{el}}{v} ds = \sum_{i=1}^N N_{el}(M_{el}(s), v'(s)) \Delta s / v_{av}. \quad (10)$$

Fig. 3. Optimal phase trajectory.

To vary the value of the undetermined Lagrange multiplier λ we used the “secant” method which implies the calculation of the value of time needed to pass the route $T(\lambda)$ for two λ values that are the initial approximation. After that, each subsequent approximation of λ is calculated by formula:

$$\lambda_{n+1} = \lambda_{n-1} - (T(\lambda_{n-1}) - t_{sp})(\lambda_n - \lambda_{n-1}) / (T(\lambda_n) - T(\lambda_{n-1})). \quad (11)$$

where: t_{sp} – is the specified time to pass the route;

The iterations should be repeated until the value of time to pass the route $T(\lambda)$ reaches the admissible deviation domain of the specified time t_{sp} .

2.5. Determining the law of the energy-efficient driving of the prototype mining dump truck

The calculations of the energy-optimal phase trajectories of the prototype dump truck were carried out for driving cases with a fully loaded vehicle when driving from the face to the concentrator and with an empty vehicle when driving from the concentrator to the face.

For performing calculations we used technical specifications of the mining dump truck given below (Table 1).

The results of the calculation of the optimal phase trajectory for the cases with vehicle driving from the face to the concentrator and with vehicle driving from the concentrator to the face are shown in Fig. 4 The control laws of the traction electric motors for both driving directions are represented in Fig. 5. Time limit for driving along the route in both straight (from the face to the concentrator) and reverse (from the concentrator to the face) directions is 1295 sec.

Table 1. Technical specifications of the dump truck prototype under test.

Parameter	Value	Parameter	Value
Gross weight, kg	50000	Final drive ratio	21,27
Curb weight, kg	25000	Coefficient of rolling resistance	0,02
Wheel rolling radius without sliding, m	0,8642	Speed losses factor, c^2/m^2	0,0009
The moment of inertia of the wheel, $kg \cdot m^2$	425	Specific cornering power	5
Forward-facing area, m^3	8,075	Moment of inertia of the body around the vertical axle (with gross weight), $kg \cdot m^2$	171000
Aerodynamic drag factor	1	Moment of inertia of the body around the vertical axle (with curb weight), $kg \cdot m^2$	85500
Efficiency of the mechanical part of the powertrain	0,95	Moment of inertia of rotating electric engine components, $kg \cdot m^2$	3,45
Power output factor	0,95	Efficiency of power converter	0,97

As seen based on the represented results, the obtained law of motion implies maintaining speed at a level of 15-20 km/h. The increase in speed on the route sections from 500 m to 1000 m and from 2300 m to 2500 m (in case of driving from the face to the concentrator, Fig. 4 a) is related to the need to climb the next grade by means of inertia forces.

Based on the obtained laws of control of the traction electric motors, we can conclude that the use of braking is kept to a minimum to reduce energy consumption (Fig. 5).

Fig. 4. The results of calculations for the 4x4 dump truck prototype: a) optimal phase trajectory for driving from the face to the concentrator; b) optimal phase trajectory for driving from the concentrator to the face.

The power consumed during driving on the route is theoretically estimated with the help of record of the dump truck driving trajectory obtained using GPS. Thus, it is determined by means of dependencies (2), (4), (5) and (10) that the power required to move the dump truck

(controlled by an experienced driver) along the route will be: 154.5 MJ when driving from the face to the concentrator and 79.3 MJ when driving from the concentrator to the face. With this, in case of driving based on the optimal law the power consumption will be: 150.1MJ when driving from the face to the concentrator and 76 MJ when driving from the concentrator to the face. Thus, we obtained the energy-optimal law of control of the traction electric motor of the dump truck.

Fig. 5. The results of calculations for the 4x4 dump truck prototype when driving along the route: a) law of control of the traction electric motor for driving from the face to the concentrator; b) law of control of the traction electric motor for driving from the concentrator to the face.

The application of the obtained law will allow us to ensure safe and energy-efficient operation of the mining dump trucks in a quarry where the level of energy consumed for driving will be more favorable compared to that one during operation of the same mining dump trucks controlled by drivers-operators. Based on the calculation results a reduction in energy consumption by 2.9 % in terms of driving from the face to the concentrator and by 4.3 % in terms of driving from the concentrator to the face was obtained. The total reduction in energy consumption for a one route cycle will be 3.4%.

3 Conclusion

The obtained laws of control of the traction electric motors when driving on the specified route will enable the safe movement of the mining dump trucks with the maximum energy efficiency and specified performance.

Based on the comparison made between the energy consumption data obtained from driving where the dump truck is controlled by an experienced driver along the given route and the energy consumption data obtained from driving in case of a software-controlled dump truck according to the optimal law on the same route, the reliability of the obtained laws and the efficiency of the developed method for determining the energy-optimal driving of the mining dump truck was confirmed.

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