Simulation based feasibility confirmation of using hybrid powertrain system in unmanned dump trucks

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Abstract. The use of medium-duty vehicles (up to 50 tons) with a simultaneous reduction in technological and operational downtime, which is achieved by automated traffic control and loading and unloading systems, as well as optimization of technological maintenance modes, can be considered a new trend in the development of mining transport. The solution that meets the requirements and current development trends is the use of medium-duty unmanned dump trucks (UDT) in the interests of the Russian coal industry. An assessment of the most important performance characteristics of UDT, such as energy efficiency indicators, is considered in this research. The purpose of the research is to confirm the feasibility of using hybrid power system (HPS) in the construction of UDT. A series HPS is considered, characterized by the use of two traction electric motors: one drives the wheels of the front axle, the second drives the wheels of the rear bogie axle. The feasibility confirmation is carried out by comparing the energy efficiency and mobility of the studied vehicle with similar, equipped with other types of powertrains by simulation methods. The presented simulation results show the efficiency of HPS application in comparison with a traditional powertrain and a mechanical transmission for UDT when driving in drive cycles similar to a given one. The use of HPS allows reducing energy consumption for motion by 20-25% due to the recovery of braking energy.

1. Introduction

Currently, more than 1.5 billion tons of coal, 80% of copper ore, two-thirds of gold, more than 50% of bauxite, phosphate, lead, zinc and other metals and minerals are mined in hundreds of the largest quarries in the world. At the same time, there is a steady tendency towards an increase in capacity and depth of quarries (the growth rate of which is 10-15 m per year) and the resulting demand for high-performance energy-efficient mining and transportation equipment. About 14 thousand units of transport equipment operate at 760 quarries in 63 countries of the world. The largest share (about 10 thousand units) are dump trucks with a carrying capacity of more than 90 tons. At the same time, mining dump trucks with a carrying capacity of 120 tons and above account for more than 60% of the total fleet of heavy vehicles [1].

The use of medium-duty vehicles (up to 50 tons) with a simultaneous reduction in technological and operational downtime, which is achieved by automated traffic control and loading and unloading systems, as well as optimization of technological maintenance modes, can be considered a new trend in the development of mining transport [2].

Requirements for the directions of development of mining transport are defined in the long-term program for the development of the coal industry of the Russian Federation for the period until 2030.
One of the directions of development is the need to develop and implement systems of unmanned mining of minerals, including the use of modern software and hardware systems integrated into the overall management system of a mining enterprise.

The solution that meets the requirements and current development trends is the use of medium-duty unmanned dump trucks (UDT) in the interests of the Russian coal industry.

An assessment of the most important performance characteristics of UDT, such as energy efficiency indicators, is considered in this research.

The object of research is an articulated six by six UDT, which gross weight is 75 tons. The purpose of the research is to confirm the feasibility of using hybrid power system (HPS) in the construction of these vehicles. A series HPS scheme is considered, characterized by the use of two traction electric motors (TEM): one drives the wheels of the front axle, another one drives the wheels of the rear bogie axle. In Figure 1b, solid lines show mechanical connections, dotted lines show electrical connections. The goal is achieved by solving the following tasks:

- estimation of energy efficiency of UDT with a HPS,
- estimation of mobility of UDT with a HPS.

Studies of the use of HPS for dump trucks are relevant at the present time, so many articles, such as [3 – 7], are devoted to this problem.

The energy efficiency of a UDT with a HPS is estimated by comparing it with a diesel analog with a mechanical transmission (Figure 1 a), as well as with a UDP using only an electrochemical storage (electric UDT, Figure 1 c).

The mobility of UDT during its movement in unprepared terrain is understood as a set of properties that determine the ability to move in given drive cycle with high speed and efficiency [8-11]. In this research, the mobility of UDT is defined by estimation of deviating of the actual UDP speed from the given one in the proposed drive cycle. Using of driving cycles for the same goals was applied by authors of studies [12, 13].

![Figure 1. UPD Scheme: a) with diesel ICE and mechanical transmission; b) with HPS; c) with electrochemical storage.](image-url)
2. Research methodology

Simulation mathematical models have been developed for estimation of the UDT energy efficiency and the ability to move under given conditions at maximum speed.

The developed mathematical models are implemented in the MATLAB/Simulink software and allow simulating UDT movement along a given driving cycle (coal mine) in order to obtain quantitative indicators of UDT energy efficiency and mobility with the selected type of powertrain.

The developed mathematical model for evaluating the energy efficiency and mobility of the UDT consists of several structural modules, including lower-level modules (battery module, generator module, ICE module, etc.) and upper-level modules (HPS module, UDT 6x6 chassis module). It is possible to synthesize simulation models of various powertrains of UDT to assess their mobility and energy efficiency using a combination of these modules. The structure of the UDT simulation model with a diesel engine and a mechanical transmission is shown in Figure 2 a, with HPS - in Figure 2 b, of the electric UDT - in Figure 2 c. The simulation model of the UDT chassis includes model of the interaction of the wheel with the supporting surface and a model of the linear motion of the UDT.

The UDT dynamic was simulated only for the case of the linear motion along a rigid road without normal reactions redistribution between the sides of the vehicle because of the little effect of the curvilinear motion on the values of capacity of energy storage devices, TEM, generator and ICE characteristics. For the same reasons the work of the suspension wasn’t taken into account during the creation of the model. The structure of the simulation model of the 6x6 UDT chassis motion is presented in Figure 2 d. The research is using the model of interaction of the wheel with the supporting surface described in the [13], because more complicated contact models [14 - 17] slow down the speed of computational experiments.

![Figure 2. Structure of the simulation model of: a) UDT with diesel engine; b) electric UDT; c) UDT with HPS; d) 6x6 UDT chassis.](image-url)
The operation of the internal combustion engine is described by the following differential equation:

\[ J_{\text{ICE}} \cdot \ddot{\omega} = h \cdot M_{\text{ICE}} - M_{\text{gen}} \]  

(1)

where \( J_{\text{ICE}} \) – moment of inertia of the internal combustion engine elements reduced to the crankshaft, 
\( \ddot{\omega} \) – angular acceleration of the ICE output shaft, 
\( M_{\text{ICE}} \) – torque developed on the ICE output shaft, which is determined by the given engine external speed characteristic (ESC), 
\( h \) – degree of ICE power use, 
\( M_{\text{gen}} \) – the generator torque.

The fuel consumption is determined by the interpolation table, depending on the ICE speed and power.

The generator and TEM are modeled by the Servomotor element from Simscape/Electronics library. The Servomotor element initial data are the dependencies of the electric machine maximum moment from the speed, the power of the losses from torque and speed and the rotor inertial characteristics. The electric machines are controlled by the mechanical torque. The electric motor model is described by the following equations:

\[
\begin{align*}
N_{el} &= I_{\text{cur}} \cdot U_{dc} \\
N_{el} &= M_{\text{mech}} \cdot \omega + N_{\text{los}}
\end{align*}
\]

(2)

where \( I_{\text{cur}} \) – current consumed by the motor, \( U_{dc} \) – DC link voltage, \( N_{\text{los}} \) – power loss, \( \omega \) – angular velocity of the electric machine shaft, \( M_{\text{mech}} \) – TEM shaft torque. Power loss \( N_{\text{los}} \) at each operating mode of the electric machine is determined in accordance with its passport characteristics.

As a model of the battery, the battery element Battery of the Simscape / Electronics library is used. The model takes into account the following parameters: rated voltage, capacity, internal resistance. The power loss \( N_{\text{los}} \) is estimated by the following relationship:

\[ N_{\text{los}} = I_{\text{cur}}^2 R_{\text{bat}} \]

(3)

where \( I_{\text{cur}} \) – current on battery, \( R_{\text{bat}} \) – internal battery resistance.

The ability to reproduce both standard driving cycles and those which are obtained by recording the parameters of the vehicle on the route is provided by the driver's model. The bus control is to maintain the set speed by adjusting the torque to the TEM with the help of a P-controller. Control action varies in the interval \([-1; 1]\]. Negative values correspond to the brake pedal pressing, positive values - the accelerator pedal pressing.

The hybrid powertrain control system model based on the input signals: the degree of accelerator and brake pedals pressing, the vehicle speed, the battery charge level, current flowed in the battery, etc., determines the modes of operation of the internal combustion engine and generator, as well as the distribution of the braking torque between the TEM and the mechanical brakes.

The initial data for simulation are shown in Table 1. The parameters of the diesel UDT gearbox are shown in Table 2.

The drive cycle is based on data of dump trucks operation in quarries and regulatory documents. It represents equal uphill and downhill driving areas (5 km). While the UPD moves uphill, it has a gross mass. While the UDT moves downhill, it has curb mass. Sections of the drive cycle differ in slope, rolling resistance and maximum speed determined from the safety requirements [18, 19, 20].

Graphs of changes in the UDT parameters and motion conditions are shown in Figure 5.

The energy efficiency evaluation of a 6x6 UDT with HPS was carried out by comparing its energy consumption in driving cycle with the energy consumption of diesel UDT when driving in the same conditions. The similar approach was used by authors of research [21].

The UDT with HPS has slightly higher dynamic characteristics than diesel UDT, so the energy consumption in the drive cycle was compared in several stages:

1) first, the simulation of the UDT motion with a diesel engine was carried out to obtain velocity time history while moving in drive cycle;

2) then, simulation of the UDT with HPS motion was carried out with maintaining the velocity obtained at the previous stage.
This approach allows to most objectively compare the energy consumption of the UDT with different powertrains, since UDT with HPS, having higher power-to-weight ratio than diesel UDT, can spend more energy by going through the drive cycle in less time with greater accelerations and speed.

**Table 1. Initial Data for UDT Motion Simulation.**

| Parameter                                           | Value          |
|-----------------------------------------------------|----------------|
| Gross Mass, kg                                      | 75000          |
| Curb Mass, kg                                       | 30000          |
| Spacing Between Centre of Mass and Front Axle, m    | 3.619          |
| Spacing Between Centre of Mass and Centre of Bogie, m | 1.552          |
| Rear Axle Spacing, m                                | 1.960          |
| Wheel Radius, m                                     | 0.922          |
| Wheel Moment of Inertia, kg·m²                      | 425            |
| Height of the Centre of Mass, m                     | 2              |
| Frontal Area, m²                                    | 8.075          |
| Aerodynamic Drag Coefficient                        | 0.9            |
| Front TEM Characteristic                            | See Fig. 3 a   |
| Rear TEM Characteristic                             | See Fig. 3 b   |
| Generator Characteristic                            | See Fig. 4     |
| ICE Characteristic                                  | See Fig. 4     |
| Front Axle Ratio                                    | 21.27          |
| Rear Axle Ratio                                     | 21.8           |
| Efficiency Factor of Axles, %                       | 0.96           |
| Gearbox Ratios                                      | See Table 2    |
| Gearbox Efficiency Factor                           | See Table 2    |
| Gear Ratio Between TEM and Rear Axle                | 1.5            |
| Nominal Normal Wheel Load, kN                       | 150            |

**Table 2. Diesel UDT Gearbox parameters.**

| Gear Number | Gear Ratio | Efficiency Factor, % |
|-------------|------------|----------------------|
| 1           | 5.615      | 98.0                 |
| 2           | 3.997      | 96.1                 |
| 3           | 2.845      | 96.0                 |
| 4           | 2.026      | 95.4                 |
| 5           | 1.429      | 96.5                 |
| 6           | 1.017      | 95.9                 |
| 7           | 0.724      | 95.4                 |
| 8           | 0.516      | 94.6                 |

**Figure 3.** Characteristics of TEM: a - Front, b – Rear.
Figure 4. Characteristics of the Generator Set.

Figure 5. UDT Drive Cycle.

3. Results

Figure 6 shows a plot of the change in speed, and Figure 7 shows energy consumption when diesel UDT moves in drive cycle. Energy consumption was determined by integrating over time the power developed by the ICE. The energy consumption of diesel UDT for a drive cycle amounted to 122.2 kW·h.
Figure 6. Diesel UDT Speed.

Figure 7. Diesel UDT Energy Consumption.

Figure 8 shows a plot of the change in speed, and Figure 9 shows energy consumption when UDT with HPS moves in drive cycle at the diesel UDT speed. The energy consumption of UDT with HPS for a drive cycle amounted to 94.8 kW·h.
Energy consumption of UDT with HPS was determined by integrating over time the power developed by the ICE and the battery. The decrease in the total energy consumption at the end of the driving cycle (when driving downhill) is due to negative battery power while it is being charged from the generator and during regenerative braking.

The maximum total energy expended for the motion of UDT with HPS is 106.6 kWh. The decrease in the total energy spent on motion towards the end of the drive cycle is explained by the recovery of braking energy during the descent, which is the last part of the drive cycle. This means that the UDT with HPS, with selected units consumes 20–22% less energy than diesel one when moving at the same conditions.

Plot of UDT with HPS energy consumption obtained when simulating motion in a drive cycle at the highest possible speed is shown in Figure 10.
According to the plot shown in Figure 10, the energy consumed during driving uphill (the falling part of the curve) is less than the total energy generated both by the generator set and recovered during driving downhill.

This means that in order to ensure the motion of UDT with HPS, the installation of a stationary charging station in the quarry is not required. The resulting "surplus" of energy (the ascending part of the curve, fig. 10) suggests that when the UDT moves in real conditions of the quarry on part of the drive cycle, the generator set may be switched off, because the energy stored in batteries will be enough.

Figures 11 and 12 show plots of changes in current and power of HPS units when the UDT moves in the drive cycle. The battery current rises to 650 A. The power of charge and discharge of the battery reaches 380 kW.

The results of actual currents and required power changes when UDT with HPS at drive cycle must be taken into account when choosing the number and type of batteries.
Figure 12. Actual Currents of UDT HPS units.

Figure 13 shows: when UDT with HPS is driving uphill, the slope of which is 9 degrees, with a movement resistance of 0.03 deviation from the required speed are insignificant and do not exceed 5 km/h. This confirms that the 6x6 UDT with HPS has sufficient mobility.

Figure 13. Speed of UDT with HPS when moving in the drive cycle.

As a result of the simulation of motion in the drive cycle of an electric UDT, a plot of energy consumption from battery was obtained (Figure 14).
According to the plot shown in Figure 14, the energy consumed during driving uphill (the falling part of the curve) is greater than the total energy generated both by the generator set and recovered during driving downhill. This means, that to ensure the motion of the electric UDT, it will be necessary to install a stationary charging station in the quarry, and when calculating the time for which useful work is performed, it is necessary to take into account the time taken to recharge the batteries.

There are plots of changes in current and power of electrical UDT units when it moves in the drive cycle in Figures 15 and 16. The battery current rises to 700 A. The power of charge and discharge of the battery reaches 400 kW.
Based on the results of a simulation of the motion of the electric UDT, a plot of the actual speed versus time during the motion at drive cycle is obtained (Figure 17).

Figure 16. Actual Currents of electrical UDT units.

Figure 17 shows: when electrical UDT driving uphill, the slope of which is 9 degrees, with a movement resistance of 0.03 deviation from the required speed are significant and exceed 5 km/h. This confirms that electrical UDT has insufficient mobility.

Figure 17. Speed of electrical UDT when moving in the drive cycle.
4. Conclusion
As part of the research, mathematical simulation of movement in the drive cycle of the diesel UDT, UDT with HPS and electrical UDT was carried out. The simulation model of the diesel UDT with a mechanical transmission takes into account gear shifting in the gearbox and efficiency of both each gear and the rest of the mechanical transmission. The simulation model of the UDT with HPS, as well as the electric one, takes into account the limitations of the charge and discharge currents of the battery, the efficiency of the TEM, generator, and axles. Preliminary results of the simulation of UDT motion in the drive cycle showed that the UDT with HPS has higher power-to-weight ratio than diesel one, therefore, to compare the energy efficiency when modeling the motion in drive cycle of the UDT with HPS, speed versus time record of the diesel UDT was used.

According to the calculated energy consumption of the UDT in the drive cycle, it is possible to determine the required capacity of the battery. As shown in the plots, the capacity of the battery of an electric UDT should be at least one and a half times greater than that of UDT with HPS, in accordance with the energy consumption in the drive cycle and the maximum charge and discharge currents occurring in the battery. An increase in the capacity of the battery causes a proportional increase in its mass, and with it an increase in the curb mass of the UDT and a decrease in its carrying capacity.

The presented simulation results show the efficiency of HPS application in comparison with a traditional powertrain and a mechanical transmission for UDT when driving in drive cycles similar to a given one. The use of HPS allows reducing energy consumption for motion by 20-25% due to the recovery of braking energy.

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