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Professional paper

PLANNING THE OPERATION OF Li-ION BATTERY-POWERED TRUCKS

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Abstract: This paper analyses the planning of operation for underground mining trucks powered by lithium-ion batteries. Trucks supplied by the companies Epiroc and Sandvik are used as examples, comparing their characteristics with equivalent diesel-engine models. These trucks have similar payload capacities and dimensions, but significant differences in available energy, demonstrating that battery-powered trucks have substantially lower autonomy. The paper describes a method for estimating the autonomy of battery-powered trucks, considering motor efficiency, energy losses, and regenerative braking. A procedure is presented for determining the energy consumption for truck movement along a known route, considering the total resistance. It is demonstrated that the lower available energy of battery-powered trucks is a major factor necessitating a different approach to planning their operation in underground mining.

Keywords: transportation planning, batteries, available energy, trucks

1 INTRODUCTION

The development of battery-powered mobile mining machines has become increasingly evident in recent years, largely driven by advancements in Li-ion battery technology. Original equipment manufacturers (OEMs) of underground mining machinery have recently integrated several battery-powered mobile machines into their product lines. This shift reflects a broader trend towards more sustainable and efficient mining operations.

Lithium-ion (Li-ion) batteries were introduced in the late 20th century and have found widespread application in the consumer electronics industry (mobile phones, portable computers, etc.). In addition, the prevailing solutions for secondary sources of electrical energy for electric vehicles are also based on lithium-ion batteries. Consequently, research related to this type of battery has focused on various lithium compounds used for making the anode and electrolyte. So far, the most widely used batteries are those

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made from lithium compounds with nickel (Ni), cobalt (Co), and manganese (Mn), as well as lithium compounds with phosphate groups (PO4). However, advances in this field are being rapidly achieved (He F., 2016).

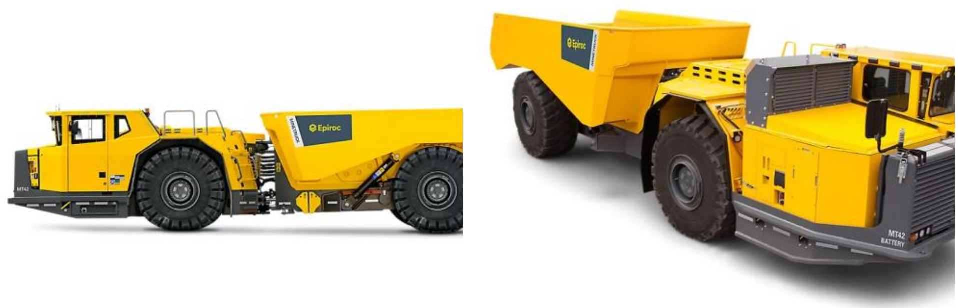
Leading European manufacturers of underground mining machinery have begun supplying users with mobile machinery powered by Li-ion batteries, as regularly reported on their websites. The reasons for this technological development include the improvement of working conditions and worker safety, reduction in ventilation requirements, lower operational costs, and more (Soofastaei et al, 2018; Energy Efficiency Opportunities, 2010). The Li-ion battery-powered machines currently offered by companies like Epiroc and Sandvik include underground loaders, trucks, and drill rigs.

Epiroc, a company involved in manufacturing machinery for the mining industry, has been producing battery-powered machines for some time now. In addition to several drill rigs, Epiroc produces two battery-powered loaders (ST14 Battery and ST18 Battery) as well as the MT42 SG Battery truck. The vehicles from this company use NMC lithium-ion batteries. Similarly, Sandvik is keeping pace with technology by producing and enhancing battery-powered vehicles. Alongside battery-powered drill rigs, Sandvik manufactures the LH518B loader and the TH550B truck. The electric vehicles from this manufacturer use lithium iron phosphate batteries ($LiFePO_4$ - LFP).

2 CONCEPT OF AVAILABLE ENERGY FOR MOBILE MACHINES

The fundamental approach of both Epiroc and Sandvik has been to adapt existing diesel-powered machines to the new technology, ensuring that the new Li-ion battery-powered machines have similar characteristics. Underground trucks can used as an example.

Epiroc produces the Minetruck MT42 and has utilized this platform to develop the battery-powered underground truck Minetruck MT42 SG Battery (Figure 1). These trucks have the same payload capacity, nearly identical engine power, and dimensions. The empty truck weight is also similar—34.5 tonnes for the MT42 and 37.7 tonnes for the MT42 SG.



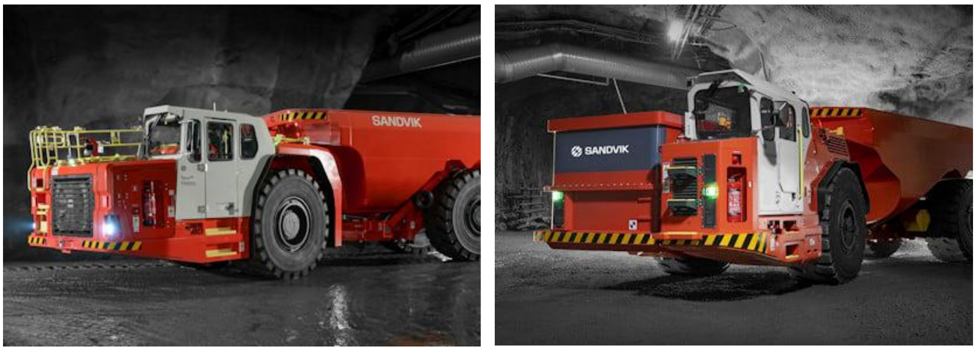
Minetruck MT42 (diesel) | Minetruck MT42 SG (Li-ion battery)

Payload: 42 t; Engine power: 399 kW; LxWxH: 10945x2689x3050 mm | Payload: 42 t; Engine power: 2x200 kW; LxWxH: 10945x2689x3095 mm

Figure 1 Underground truck by Epiroc (www.epiroc.com)

Sandvik offers the diesel-powered underground truck Toro TH551i, on the basis of which the TH550B truck, powered by Li-ion batteries, was developed (Figure 2). These trucks also have similar payload capacities and dimensions, as well as comparable empty truck weights (46.9 tonnes for the TH551i versus 49.6 tonnes for the TH550B). The only significant difference is in the engine power, as the diesel engine power is 515 kW, while the TH550B truck has four motors located in wheel hubs, each with a power output of 180 kW (for a total of 720 kW).

It can be observed that the characteristics of trucks powered by Li-ion batteries are largely aligned with those of diesel-powered trucks.



Toro TH551i (diesel) | TH550B (Li-ion battery)

Payload: 51 t; Engine power: 515 kW; LxWxH: 11500x3200x3200 mm | Payload: 50 t; Engine power: 4x180kW; LxWxH: 11000x3350x2900 mm

Figure 2 Underground truck by Sandvik (www.sandvik.com)

The main difference between diesel-powered trucks and those powered by Li-ion batteries is the available energy to perform work. Epiroc's MT 42 truck has a diesel fuel tank capacity of 580 Liters, whereas Sandvik's Toro TH551i truck has a tank capacity of as much as 840 Liters. To determine the available energy from these quantities of fuel, the lower heating value of diesel, which is 35.9 MJ/l (Davis S.C., Boundy R.G., 2022), will be used. On the other hand, the mentioned companies have provided the following battery capacities for their battery-powered trucks: 375 kWh for the Epiroc Minetruck MT42 SG and 354 kWh for the Sandvik TH550B.

To compare the available energy of these machines accurately, it is necessary to consider the efficiency of the drive motors. The efficiency of internal combustion engines running on diesel fuel is about 30%, while the efficiency of AC synchronous electric motors is approximately 95% (Đajić, 1981; Aleksandrović, 2017). Table 1 lists the available energies (in GJ) for the trucks mentioned above, for both types of used energy, with and without accounting for motor efficiency.

Table 1 Comparison of Available Energy (in GJ) for Diesel-Powered and Battery-Powered Trucks

Available Energy (GJ)	**Epiroc MT 42**	**Sandvik Toro TH551i**
Diesel (overall)	20,822	30,156
Diesel (Engine efficiency – 30%)	6,247	9,047
	MT 42 SG	TH 550B
Li-ion batteries (overall)	1,350	1,274
Li-ion batteries (Engine efficiency – 95%)	1,283	1,211

Conversion: 1 kWh = 3,6 MJ

It can be observed that underground trucks powered by Li-ion batteries have significantly lower available energy compared to their diesel-powered counterparts. The MT 42 SG has approximately 20% of the available energy of the Epiroc MT42, while the TH 550B has only about 13% of the Toro TH551i's energy capacity. The lower available energy of the TH 550B is primarily due to the large fuel tank of the Toro TH551i. Additionally, Sandvik's batteries are based on LFP (lithium iron phosphate) Li-ion cells, which have lower energy density compared to the NMC cells used by Epiroc (a drawback compensated by greater stability and longer lifespan).

Additionally, the low efficiency of internal combustion engines has been mitigated by increasing the fuel tank capacity.

3 MINE TRUCKS PERFORMANCE PLANNING PROCEDURE

The standard procedure for calculating the movement of vehicles on pneumatic tires is based on the relationship between engine power (N_m), effective traction force (P_t), and vehicle speed (v).

$$N_m = \frac{P_t \cdot v}{\eta_p} \; [W] \; \rightarrow \; P_t = \frac{N_m \cdot \eta_p}{v} \; [N] \quad (1)$$

where:

η_p – power transmission efficiency coefficient from the engine to the traction wheels.

The traction force determined in this manner is parallel to the ground surface and directed in the rolling direction of the wheel. Moreover, its maximum value is constrained by the wheel-to-surface adhesion conditions and depends on the adhesive weight of the vehicle (L_a) and the adhesion coefficient (ϕ).

$$P_{t\,max} \leq L_a \cdot \varphi \; [N] \quad (2)$$

On the other hand, the traction force must be sufficient to overcome the total resistance (W_u) that opposes the movement of the vehicle.

$$P_t \geq W_u = W_o + W_v \pm W_n + W_r \pm W_i \quad (3)$$

The total resistance is the sum of primary and secondary resistances, where the primary resistances include rolling resistance (W_o) and aerodynamic drag/resistance (W_v), while the secondary resistances are grade resistance (W_n), curve resistance (W_r), and inertia resistance – accelerating/braking (W_i). The primary resistances act continuously during the motion of vehicle, whereas the secondary resistances vary depending on route characteristics (grade and curve resistance) and vehicle movement conditions (inertial mass resistance—acceleration or deceleration). These resistances are expressed in Newtons.

In practice, these resistances are calculated as the product of the total vehicle weight (L), expressed in kilonewtons, and the specific resistance values, expressed in N/kN, except for aerodynamic drag/resistance. An overview of the calculations for individual resistances is provided in Table 2.

Table 2 Overview of primary and secondary resistances for vehicle in motion (Simonović, 1972)

Item	Resistance [N]	Specific resistance [N/kN]	Remark
Rolling resistance	$W_o = L \cdot w_o$	w_o	Empirical value.
Aerodynamic drag	$W_v = \frac{1}{2} \cdot c \cdot \rho \cdot F \cdot v^2$	-	No specific value.
Grade resistance	$W_n = \pm L \cdot w_n$	$w_n = \pm i$	*i* is route grade in ‰.
Curve resistance	$W_r = L \cdot w_r$	$w_r = 30 \cdot \frac{200 - r}{200}$	*r* is curve radius.
Inertia resistance	$W_i = \pm L \cdot w_i$	$w_i = 102 \cdot (1 + \varepsilon) \cdot a$	ε is inertia coef. of rotating parts; *a* is acceleration/deceleration.

This approach allows us to divide the entire vehicle route into segments in which the sum of individual resistances remains constant. In other words, the route (S) consists of (n) segments where, on each segment, the sum of primary and secondary specific resistances is constant. This can be expressed as follows:

$$S = \sum_{j=1}^{n} s_j \ [m] \ \ where\ for\ each\ s_j\ it\ follows\ \ w_{uj} = const\ [N/kN] \qquad (4)$$

Based on the assumption that the segment lengths are known, along with the specific conditions of the route (w_o, w_n, w_r, etc.), the fundamental problem in the analysis of truck transport is thus reduced to determining the speed of truck movement along individual segments, and consequently, the time required for this movement. The result of such an analysis is the time needed to complete one cycle of truck movement along the given route.

The procedure described is suitable for determining the haulage capacity of a single truck, which is then further used to determine the required number of trucks to achieve the designed overall haulage capacity. So far, this type of calculation has been primarily applied to trucks equipped with diesel IC engines.

4 LI-ION BATTERY POWERED TRUCKS OPERATION PLANNING

The above-described approach to haulage planning for trucks with Li-ion batteries will not provide valid results, as it does not account for the available energy for truck movement. In the case of diesel-powered trucks, the common practice is to refuel the tank with the necessary amount of fuel for a single shift or workday. Due to the high thermal value of diesel fuel and its substantial available energy, diesel trucks have significant autonomy, allowing them to adapt to technological requirements during operation, such as changes in the travel route.

The energy stored in truck batteries is significantly lower than the energy available in diesel-powered trucks and is evidently insufficient for autonomous operation of these machines during a single shift. Mentioned mining equipment manufacturers have developed battery-swapping systems, which allow the replacement of a discharged battery with a fully charged one. This process enables the truck to continue operations; however, it must be accounted for in planning, as additional time is required for the truck to deviate from its usual route, travel to the charging station, replace the battery, and return to regular operation.

However, the question remains: how much work can be done with the energy stored in the battery?

The following section will describe the procedure for evaluating the autonomy of Li-ion battery-powered trucks along a predefined route. This procedure is based on the aforementioned parameters and is a function of the available battery energy.

As shown in equation (3), the total resistance can also be viewed as the traction force—a force acting at the center of the wheel, directed along the direction of motion and parallel to the surface.

Equation (4) indicates that the truck's route can be divided into segments, with each individual segment having a constant value of total specific resistances. The following should be noted:

- Trucks designed for underground mining operations feature a two-part chassis, two axles, and are most commonly equipped with four-wheel drive (axle configuration 4x4, as shown in Figures 1 and 2). Loaded trucks experience a higher load on the rear axle, whereas empty trucks have a greater load on the front axle. In the following analysis, it is assumed that the load is evenly distributed across both axles and that the weight is uniformly distributed between the left and right wheels—resulting in an equal load on all wheels.
- The truck driving cycle essentially consists of hauling the load to the discharging site and returning the empty truck to the loading location. Therefore, when determining the total resistance during load hauling, both the

vehicle weight and the load weight must be considered, whereas for the return trip to the loading location, only the vehicle weight is taken into account (He et al., 2013).

Total resistance value is obtained by multiplying the specific resistances in equation (4) by the truck's weight. This resistance will be considered as the traction force exerted by the wheel on the vehicle, which remains constant along a single segment.

$$P_{t\,j} = L \cdot w_{uj} \;\; [N] \tag{5}$$

where:

P_{tj} – is a traction force along segment s_j (N).

L – is a weight of the truck (kN), where, depending on circumstances, this can be weight of loaded truck (weight of the truck combined with the weight of the load) – L_{pu} or just the weight of the truck – L_{pr};

w_{uj} – is sum of specific resistances along the segment s_j (N/kN);

The work (A_j) done by the traction force P_{tj} during movement along the segment s_j is the product of these two quantities, while the total work along the entire route is the sum of the work performed across individual segments. The work required for the movement of a loaded truck (L_{pu}) and an empty truck (L_{pr}) along the complete route can be determined as follows:

$$A_{pu} = \sum_{j=1}^{n} A_{j\,pu} = \sum_{j=1}^{n} s_j \cdot P_{tj} = \sum_{j=1}^{n} s_j \cdot L_{pu} \cdot w_{uj} \; [J] \tag{6a}$$

$$A_{pr} = \sum_{j=n}^{1} A_{j\,pr} = \sum_{j=n}^{1} s_j \cdot P_{tj} = \sum_{j=n}^{1} s_j \cdot L_{pr} \cdot w_{uj} \; [J] \tag{6b}$$

The total work, in mechanical context, during the truck's movement over one driving cycle along a predefined route, is obtained by summing equations (6a) and (6b):

$$A = A_{pu} + A_{pr} \;\; [J] \tag{7}$$

It should be emphasized that, on certain segments of the route, the sum of specific resistances (w_{uj}) may have a negative value. This can occur when the truck is moving downhill (due to a decrease in its potential energy) or during deceleration (due to a reduction in its kinetic energy). In both cases, the truck operates in a brake mode, resulting in the replacement of the traction force with a braking torque, i.e., a braking force that also acts at the center of the wheels, is parallel to the surface, but is directed opposite to the vehicle's motion.

The truck's movement is not powered by battery energy on segments where $w_{uj} < 0$. Therefore, to accurately determine the autonomy of battery-powered trucks, these segments must be excluded from equations (6a) and (6b), and consequently from expression (7), leading to the derivation of expressions (8a), (8b), and (9):

$$A'_{pu} = \sum_{j=1}^{n} A_{j\,pu} = \sum_{j=1}^{n} s_j \cdot P_{tj} = \sum_{j=1}^{n} s_j \cdot L_{pu} \cdot w_{uj}\ [J] \qquad , for\ w_{uj} > 0 \qquad (8a)$$

$$A'_{pr} = \sum_{j=n}^{1} A_{j\,pr} = \sum_{j=n}^{1} s_j \cdot P_{tj} = \sum_{j=n}^{1} s_j \cdot L_{pr} \cdot w_{uj}\ [J] \qquad , for\ w_{uj} > 0 \qquad (8b)$$

$$A' = A'_{pu} + A'_{pr}\ \ [J] \qquad (9)$$

Work A' obtained from equation (9) represents the energy consumed for the truck's movement along the route during one cycle, which is supplied from the battery. This energy can be compared to the energy stored in the battery to assess the truck's autonomy. Similar energy analyses of vehicle movement is already common practice and is used for transport optimization (Energy Efficiency Opportunities, 2010).

It is essential to consider the limitations related to the amount of available energy that the battery can supply, as well as the losses incurred during transmission and conversion:

- Manufacturers of Li-ion batteries and researchers do not recommend their complete discharge, as it significantly reduces their lifespan (Han, 2019). In other words, when planning the operation of battery-powered trucks, the full battery capacity should not be assumed as available.
- Losses in electrical power transmission occur due to Joule heating and Ohmic resistance, both of which manifest as heat dissipation. These losses are present in all components of the electrical system, including the battery, inverters, and cables.
- Losses in the electric motor: Nearly all vehicles powered by Li-ion batteries use synchronous electric motors with permanent magnets, which have a high efficiency. The efficiency of these motors ranges from 92% to 97% (Dambrauskas, 2020).
- Losses in mechanical power transmission: These losses occur in the components of the mechanical power transmission system from the electric motor to the wheels.

The battery supplies energy to other consumers on the truck, meaning that energy is not solely used for vehicle propulsion. The largest consumer, aside from the traction motors, is the auxiliary electric motor that powers the hydraulic pump. The power of the auxiliary motor on the trucks mentioned above is 160 kW (Epiroc) and 200 kW (Sandvik). Other consumers include the air conditioning system in operator cabin, lighting units, sensors, instruments, and similar.

One of the strategies for increasing the autonomy of electric-powered vehicles is the implementation of regenerative braking system, which is standard equipment on mining vehicles, including the trucks discussed in this study. This system enables the synchronous electric motor with permanent magnets to operate in generating mode during braking, producing electrical energy by reducing the truck's kinetic energy. The generated electrical energy is then converted and stored in the battery [Islameka M. et al., 2023].

Research on the impact of regenerative braking systems in electric vehicles indicates a possible increase in autonomy (range) of 11% to 22% (Wager et al., 2022; Berjoza, 2022), with system efficiency being higher at greater speeds, characteristic of passenger vehicles in public transportation. Mining trucks operate at relatively low speeds. In underground mining operations, vehicle speed is typically restricted (most often to 10–15 km/h), resulting in short braking and stopping times, thereby limiting the energy recovery potential from braking at a stop. Significant energy regeneration effects are only feasible on route segments where the vehicle moves downhill in braking mode.

Despite these advancements, friction brakes remain an indispensable component of underground mining trucks and other mobile mining machines as a safety measure.

Finally, the truck's autonomy or the number of cycles (*n*) that a battery-powered truck can complete on a predefined route can be determined using the following equation:

$$n = \frac{E_{bat}}{A' + E_{aux} - E_{rbs}} \; [cycles] \tag{10}$$

where:

E_{bat} – energy stored in the battery or battery capacity (J);

A' – energy supplied from battery for motion of the truck during a one cycle (J)

E_{aux} – energy supplied to the auxiliary motor and other consumers during a single cycle (J);

E_{rbs} – energy recovered with regenerative braking system and restored in the battery, during a one cycle (J);

Thus, after completing (n) cycles, the truck's battery will be nearly discharged and will need to be replaced to prevent excessive over discharge and potential damage. Due to possible circumstances that may cause delays or interruptions in truck movement within an underground mine, it is expected that a battery replacement strategy will be adopted once its state of charge (SoC) drops to 25–30% to prevent degradation. While this approach would have a positive impact on battery lifespan, it would also negatively affect the realization of the designed haulage capacity due to more frequent battery replacements.

5 CONCLUSION

Battery-powered trucks are already a reality in the underground mining industry. Although significant differences from internal combustion engine trucks may not be immediately apparent, certain characteristics of this technology necessitate a different approach when planning their operation, with the most crucial one is the lower available energy of the vehicle. This underscores the importance of conducting a thorough energy analysis of truck movement.

Determining the energy required for vehicle movement is mechanically straightforward. However, a systematic approach to this task – aimed at assessing the haulage capacity of the truck along a predefined route – requires a structured energy analysis of all resistances, consumers, and losses.

This paper provides the methodology for determining the energy required for truck movement during a single driving cycle, based on primary and secondary resistances. It has been demonstrated that the energy analysis in this case includes only those segments of the route where the sum of all resistances is greater than zero, as battery energy is utilized on these segments. Additionally, constraints related to battery capacity, other energy consumers on the truck, and the regenerative braking system have been highlighted. Finally, an equation for determining truck autonomy, specifically the number of cycles a truck can complete with a fully charged battery, has been provided.

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