HEAT GENERATION IN BATTERY ELECTRIC UNDERGROUND HAUL TRUCKS

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ABSTRACT

Battery electric mining equipment has been gaining considerable attention from mining operations across the globe and is being implemented to a significant degree in Northern Ontario. This shift is primarily driven by the obvious benefit of eliminating diesel engine emissions. Current regulations for ventilation system design are driven almost completely by particulate matter from diesel exhaust, but with the transition to battery equipment, ventilation design must consider new factors to drive the ventilation requirements. For deep mines, the main driver of ventilation requirements will most likely be heat. The initial thought when estimating heat generation from a battery electric machine would be to reference the installed power and use utility factors in the same way diesel equipment heat is estimated. This is not correct. Battery electric equipment produces significantly less heat than an equivalent diesel machine. The obvious difference is the efficiency of the motor as compared to a diesel engine. However, the reduction in heat generation is much greater than the expected ⅔ from this efficiency improvement. Regenerative braking and other system capabilities reduce heat generation by recapturing the potential energy of the truck and any additional mass returned down-ramp. This paper will discuss modeling and analysis of the heat generated in a 40 tonne battery electric haul-truck and compare it with heat from a diesel powered equivalent. The results will provide guidance to ventilation system designers and attempt to redefine how ventilation requirements are calculated.

KEYWORDS

heat generation, battery electric, BEV, haultruck, ventilation, Artisan Vehicles

INTRODUCTION

Diesel particulate emissions from mobile equipment is arguably the most dangerous hazard in the mining industry. There are now multiple studies that show that DPM is a carcinogen and the cause of many negative health effects. As more conclusive studies are completed, the governments around the world are tightening restrictions on DPM concentrations and ventilation requirements. This is driving manufacturers to produce machines with lower emissions and driving the development of new technologies that reduce or eliminate these emissions entirely. The most promising alternative to diesel that is currently available is battery electric drive equipment. Battery equipment is gaining significant adoption particularly in Northern Ontario Canada [Paraszczak]. With the adoption of electrically driven machines there is a need for the ventilation design engineers in the industry to adapt to new methods for determining ventilation and cooling requirements. With a primarily diesel fleet, ventilation is almost invariably determined by the need to address the emissions of the engines underground. In some regulations the ventilation is proportional to the installed horsepower. In others, the requirement is driven by the actual emissions of the installed engines. In most cases, the heat load is secondary to the emissions control. However, as more electric equipment is used, the ventilation requirement will be driven by new factors. In many underground mines, particularly deeper mines, heat will become the main driver for ventilation requirements.

Current Methodology

Ventilation engineers faced with the need to size ventilation systems are looking to existing methods of approximating heat load based on installed engine power and utilization factors. Multiple authors have stated the basic physics of heat generation, that all energy consumed that does not do work against gravity ends up as heat. [Veraschin] This is based on the first law of thermodynamics and is inarguable in this case, however, these authors fail to describe the impact of the one caveat they mention. What happens to the energy that does work against gravity? Kerai and Halim reference the difference in efficiency of the power plant (engine vs motor) and use that as a scale factor to adjust the heat load of a machine based on the power rating of its electric motors. This method makes a few erroneous assumptions. First is that the machine efficiency(the other systems in the truck) is the same for the electric drive machine and the diesel machine. Second is that the motor in the machine is sized to match the average requirement in the same way an engine is sized. Third is that there is no method of recapturing and storing energy in the electric machine. Let's discuss these in more detail.

1) Machine efficiency is typically much improved by due largely to the flexibility and capabilities of electric drive technology. Torque converters, auxiliary pumps, alternators and even transmissions can either be dramatically improved or removed entirely in a BEV. The GMG BEV guideline posits that the BEV heat output is 20% of due to overall efficiency of power plant and driveline but estimates that the engine vs motor efficiency accounts for only 52% of that reduction comes from the battery and motor vs engine.
2) The current method of heat load estimation utilizes the installed power rating of the engine as the base of the analysis. When there is no ventilation requirement penalty proportional to the installed power, OEMs can increase the power to provide much more than is typically required. The result is significantly more capability, but not necessarily a higher average power output or utilization. In the case of a loader, a higher power capability may allow the loader to fill the bucket with just one push into the muck-pile. A lower powered machine may take multiple attempts to fill the bucket, thus requiring more total energy and producing more heat than the higher power capable machine. A heat generation estimate reliant on the installed power would estimate that the higher power machine produced more heat when in fact the lower power machine produces more heat.
3) The ability to recapture kinetic and gravitational potential energy has a huge impact on total energy efficiency and heat generation. This will be the focus of this paper.

The initial approach to comparing heat generation between motor and engine driven machinery is to compare the efficiency of the prime mover. Electric motors are typically as much as three times the efficiency of a diesel engine. Thus, the initial estimates typically start at that ratio for reduction in heat. Let's look in more detail at the efficiencies of the typical prime movers to add some detail to that estimate.

Electric Motors:

Electric motors have an efficiency ranging from 85-98% based largely on the type of motor. Induction motors typically have a lower efficiency due to the rotor currents required to generate a magnetic field. Permanent magnet motors are typically 93-98% efficient because they don't require any current flow to generate the rotor magnetic field. The variation in efficiency is a result of how well the motor design prevents stray induced currents in the steel of the machine. These eddy currents are typically controlled by laminations in the rotor and stator. More laminations results in a more efficient motor, but increases cost. On average, a permanent magnet motor of a size and quality useful for a mining truck would yield an efficiency close to 95%. The inverters that drive these motors are typically on the order of 98% efficient, so the combined motor and inverter net about 93%.

Diesel Engines:

The most efficient single cycle internal or external combustion engine achieved an overall energy conversion efficiency of 54.4%. In smaller engines for mobile applications, friction and other pumping losses further reduce that efficiency to what is typically seen in mobile engines. As engines increase in size, fuel delivery losses, oil circulation losses, and to a certain extent friction and viscous losses in the system become a lower fraction of the produced power, thus increasing the efficiency as size increases. Smaller engines for automotive applications range in the 35-45% efficiency range, while large stationary or marine engines can get up to about 50% efficiency. Most engines for mine trucks in this class have an efficiency between 30-37%.

Driveline and Auxiliary differences:

The traction motor efficiency has the largest effect on heat generation from the haultruck, however, there are additional factors affecting the overall system efficiency. Switching to batteries and electric motors for tractive power makes enables improvements to other systems. Since electric motors do not have to idle to continue operating, the motor can be stopped when the truck stops. This means that no clutch or torque converter are needed. In diesel machines, there is only one source of mechanical power, so all of the other systems on the truck draw mechanical power from the engine. This includes the alternator/generator for 24 V accessory power, the hydraulic pump for work functions like steering and box cylinders, cooling pump for cooling the engine, transmission pump for providing cooling, lubrication and clutch pressure for the transmission. In a battery powered machine, these loads are either unnecessary or are provided by independent electrically driven systems. The independent systems can be designed to only draw as much power as needed and don't have to be supplied by an engine that is changing speed based on driving requirements. This allows significant optimization of these accessory systems and improves overall truck efficiency. The net of all the improvements in driveline efficiency and auxiliary system efficiency as well as idle reduction result in a ratio of closer to 1:5 or 20%. [GMG BEV guideline] This efficiency difference directly affects the heat generation on the climbing part of a haulage cycle, but it's the descent of the ramp that brings about the most critical and least obvious change to the total heat generation. To best understand this, we will need to model both the conventional diesel truck and the battery electric truck.

METHOD

To accurately compare the heat production of a diesel truck and a battery electric truck we need to create a defined scenario that we can easily calculate. Looking at just the ramp haulage cycle eliminates the variables of idle losses and other usage cases that can vary from application to application. This approach will compare the machines while doing what they were designed to do, hauling ore. Inclusion of idle in the cycle would show further reduction in heat for the battery truck, so neglecting this tends to make the results more conservative in addition to simplifying the analysis. We will look at the energy flow from a lumped parameter model that will simplify the analysis so that we don't need to know all the details of what is causing each loss. There are just few key energy equations from basic physics and a few simple assumptions we must clarify. First is the equation for gravitational potential energy [1]. Energy created or work is done when a force creates movement against a force. The force of gravity is the acceleration due to gravity, g, times the mass of the object. As you lift an object, you do work against gravity proportional to the distance you move the object vertically.

$$Energy_{potential} = mass \times g \times height \qquad [1]$$

The second is that power is energy/time, which is to say that power is the flow of energy from one form to another. Thus, the rate of heat generation from a truck can be represented by a power, as can the flow of energy into the potential energy of the mass components of the truck, the empty truck and the load it is carrying.

To determine where all the energy goes and what energy ends up as heat, we will assume that no energy enters or leaves the system. The system boundary in this case is a fully insulated ramp section containing a truck at the bottom of the ramp section with fuel or battery energy on board and a full load in the box. The first law of thermodynamics states that energy is conserved, so in this model, we are looking at the changes in the form of the energy present at the start of the cycle. We assume that no heat goes into the rock, none comes from the rock, no air enters the system or leaves the system. All the energy in the system is present at the start of the analysis and at the end.

The energy at the bottom of the ramp is the chemical energy in the battery and the diesel fuel in the tank. The other possible energy states in the system are heat, potential energy of the truck, and potential energy of the load. We will neglect the kinetic energy of the truck by assuming that we start at rest and end at rest. The kinetic energy of the slow moving truck is not very large, so even while the truck is in motion, this has little impact on the model. (kinetic energy of the loaded truck is 132 W×h).

The battery electric truck model is based on the Artisan Z40 40 tonne haultruck. This model was created to represent the effects of ramp angle, load and speed on the energy consumption and heat generation of the Z40. This model was validated by comparison to actual test results from a battery truck in service at the Macassa mine in Kirkland Lake, Ontario, Canada. The model calculates the power required to overcome tire losses, driveline losses, aerodynamic losses and changes in gravitational potential energy.

Modeling the heat generation of the diesel truck was more complicated than the model of the Z40. As a manufacturer of battery electric equipment, we have access to actual test data to validate our models and ensure good correlation and the analysis presented here is based on actual test results from our Z40 battery electric haultruck. Diesel combustion is also a much more complicated process. The fuel that is combusted in the cylinder of the engine is broken down and combined with oxygen and other molecules in the fuel and in the air to create heat and other molecules. The standard chemical equation of combustion converts fuel and oxygen into carbon dioxide and water. Unfortunately, true combustion does not yield only these ideal exhaust components. There are numerous other chemicals produced, hence the need for emissions control and the push to find alternative means to provide motive power. According to Resitoglu, Altinisik and Keskin, the exhaust is made up of 67% N_2, 12% CO_2, 11% H_2O, and 9% O_2. The remaining 1% is made up of CO, HC, NO_x, SO_2, and PM. The molecules in the 1% of exhaust gas have little impact on the energy equation, allowing us to assume that >99% of the fuel energy is converted to either heat or mechanical energy.

The amount of power required to climb the ramp is an important part of the model of the diesel machine. For this analysis, a reference vehicle was used. The Atlas Copco (now Epiroc) Minetruck MT436LP is a low profile articulated underground haultruck with a 32,650 kg capacity. The datasheet for the MT436LP includes the engine power rating, the fuel consumption at full load, and the full load travel speed on various grades[436LP datasheet]. With these numbers, we can calculate the rate of energy consumption of the standard truck.

First we need to determine the amount of engine power used to raise the gravitational potential energy. We can determine from the datasheet gradeability curves that the required power to ascend with a full load of 32,650 kg in a truck weighing 30,600 kg at 5.2 kph on a 16% grade is 298 kW(engine power rating). Using these values in the equation [2] below, we have the portion of power required to raise the combined mass at the speed the MT436LP is capable of using full engine power. The actual calculation is shown in equation [3]

$$Power_{gravity} = mass \times g \times \frac{dh}{dt} \quad [2]$$

$$Power_{gravity} = 63{,}250kg \times g \times \sin(\text{atan}(16\%)) \times 5.2\frac{km}{hr} = 141kW \quad [3]$$

By subtracting the power required to raise the mass of the machine and load from the engine power rating, we can determine the power required to overcome machine losses and supply the machine's auxiliary systems. See equation [4] below. This combined loss and auxiliary power consumption can be used to scale the diesel truck energy consumption for our analysis.

$$Power_{losses} = Power_{engine} - Power_{gravity} = 298kW - 141kW = 157kW \quad [4]$$

At this power, the fuel flow rate is 95 L/hr. This fuel flow for a power output of 298kW is equivalent to 29.3% engine efficiency. Paraszczak and Svedlund, et. al. reference energetic efficiency for haultrucks of 30-35%, which supports this value. The calculation is shown in detail in equation [5] below.

$$\gamma_{engine} = \frac{Power_{mechanical}}{\rho_{diesel} \times HHV_{diesel} \times Fuel\ flow} = \frac{298kW}{0.846\frac{kg}{L} \times 12.67\frac{kWh}{kg} \times 95\frac{L}{hr}} = 29.3\% \qquad [5]$$

The weight of the diesel truck was assumed to be 34,000 kg, which is on par with the Sandvik TH540 (34,700 kg) and the Epiroc MT42 (34,500 kg). Using equation [2] above and scaling up to a 40,000 kg load with a base weight of 34,000 kg and a travel speed of 8 kph, the gravitational power requirement becomes 239 kW. Adding the 157 kW of losses, the new total required mechanical power is 396 kW. Dividing by the engine efficiency, the fuel power required is 1352 kW.

$$Power_{fuel} = \frac{Power_{losses} + mass \times g \times \frac{dh}{dt}}{\gamma_{engine}} = \frac{157kW + 74{,}000kg \times g \times \sin(\text{atan}(15\%)) \times 8\frac{km}{hr}}{29.3\%} = 1352kW \qquad [6]$$

The power going to heat is the total fuel power supplied to the engine, minus the power going to the potential energy of the combined mass of the truck and load. This is shown in equation [7] and calculated in equation [8] below.

$$Power_{heat} = Power_{fuel} - Power_{gravity} \qquad [7]$$

$$Power_{heat} = 1352kW - 74{,}000kg \times g \times \sin(\text{atan}(15\%)) \times 8\frac{km}{hr} = 1113kW \qquad [8]$$

RESULTS/DISCUSSION

The following images will depict each stage in the operation of the truck on a typical ramp haulage cycle. The potential energy of the truck and load are depicted as a green highlight on the body. The heat energy is depicted as a growing cloud of red around the truck, The direction of power flow is indicated by an arrow up or down depending on the operating mode.

At the start of the cycle, the truck is loaded with 40 tonnes of material and the fuel tank is filled with just enough fuel to reach the top of the ramp. The load is at the lowest elevation of the cycle, so its gravitational potential energy is zero. The amount of fuel is just a small portion of the full fuel energy capacity. A full tank would contain 4700 kWh equivalent energy, but starting with just enough to reach the top cleans up the model and minimizes the complexity. The initial energy state is depicted in Figure 1 below.

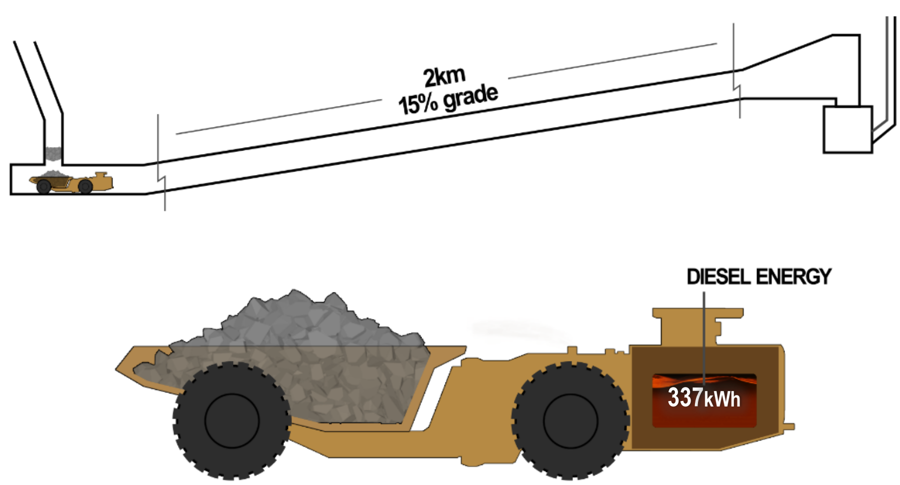

Figure 1. Initial Energy State

Once the truck begins ascending the ramp, the engine starts converting the liquid fuel into mechanical power to propel the machine, overcome losses, and provide for the auxiliary system functions like the alternator and hydraulics. These are shown in Figure 2 below.

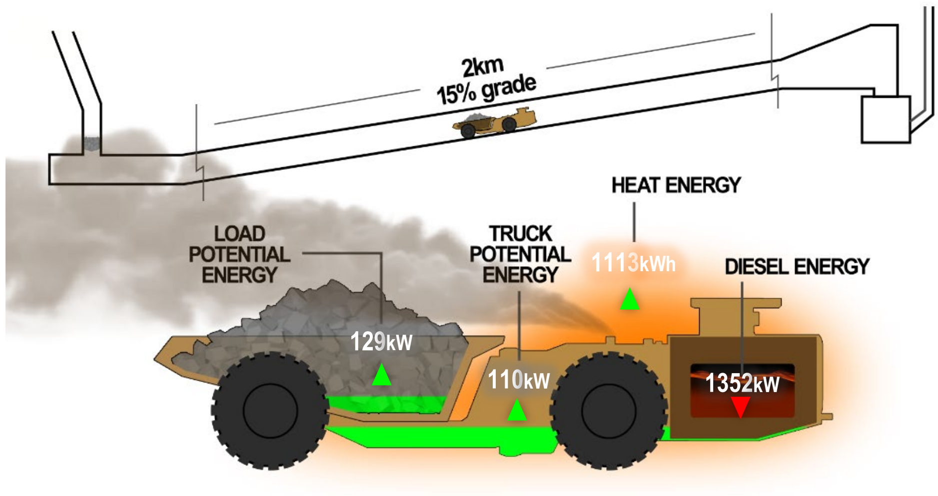

Figure 2. Diesel-climbing loaded

At the top of the ramp, the mechanical power of the engine has raised the energy state of the truck mass and the load mass. The load mass is dumped into the load pocket and it no longer interacts with the system. The potential energy of the load does not become heat. Note that 17.5% of the total energy consumed climbing the ramp is actually stored as potential energy during this part of the cycle. The 32kWh of the load is dumped and stays stored in the load, and the truck potential energy is going to be dissipated in the return trip down the ramp but at this point in the cycle the energy is not in the form of heat. The Energy state at the top of the ramp is shown in Figure 3.

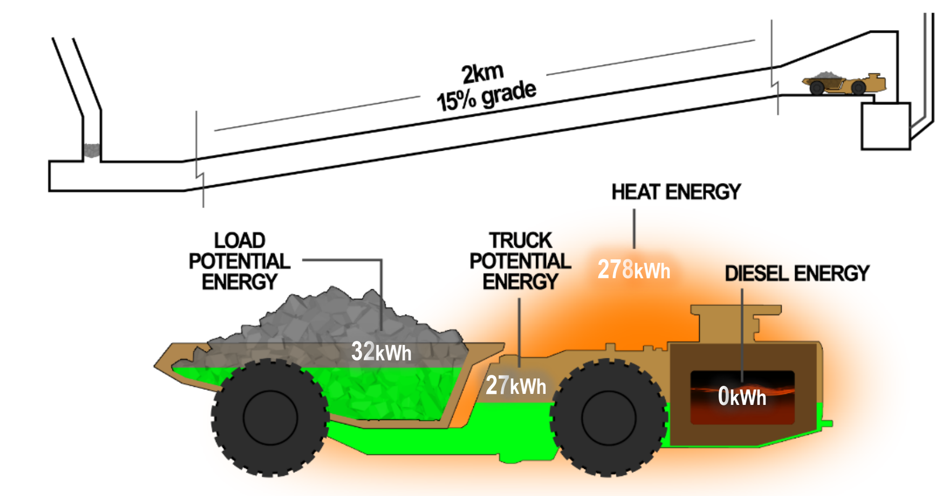

Figure 3. Diesel - Top energy state

On the diesel trucks return trip down the ramp the engine is used for compression braking to slow the descent. In this way, the 27kWh of potential energy of the truck mass is converted entirely to heat. There is no storage of energy on the truck to recapture it. Most of the energy is converted to heat through pumping losses in the engine, while some energy is used to run lights and auxiliary electrics and hydraulics for steering and cooling. Regardless of the path through these systems, all the energy is converted to heat. This is shown in Figure 4.

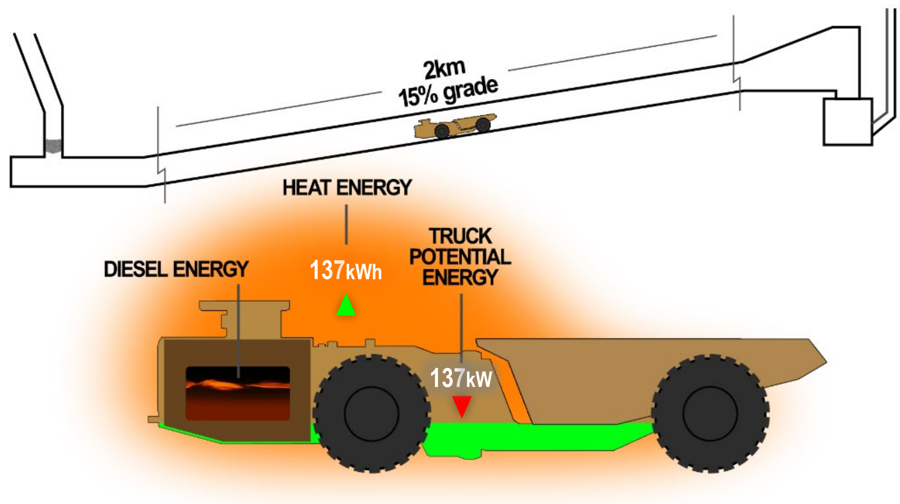

Figure 4. Diesel - Descending empty

Once the machine reaches the bottom of the ramp and completes the cycle, the relative potential energy of the truck mass is zero since it has returned to the original elevation and the 27kWh of potential energy in empty truck is fully converted to heat. The heat energy produced is 308kWh.

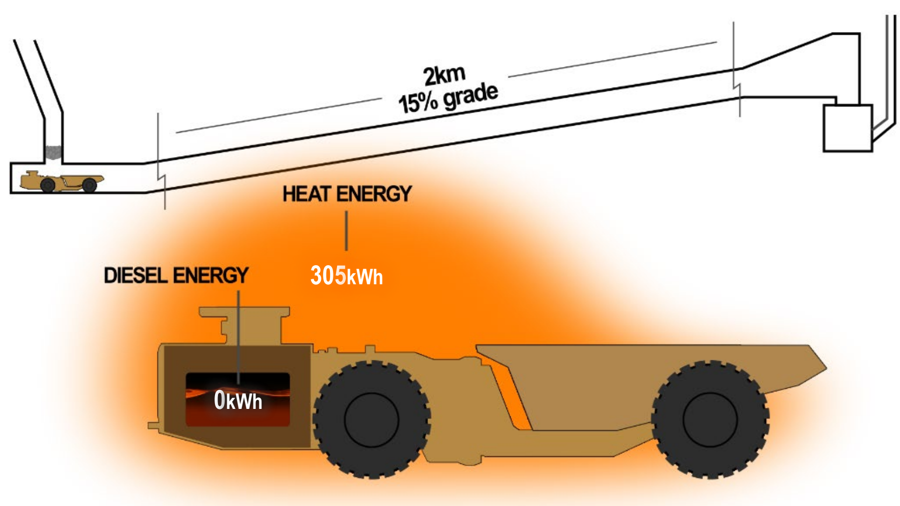

Figure 5. Diesel - End energy state

Next, we consider a battery electric haul truck. Artisan Vehicles is the manufacturer of the Z40, a 40 tonne capacity articulated battery electric underground haultruck. At the start of the cycle, the truck is loaded to capacity with material and is located at the bottom of the 2km 15% ramp. For this analysis we will assume that the battery starts with just enough energy as required to reach the top of the ramp fully loaded. In actual use, the battery would be maintained somewhere between 10% and 95% SOC to increase cycle life of the battery. Treating the stored capacity as just the required amount will simplify the analysis and is similar to the way the diesel truck was analyzed. The initial energy state is captured in Figure 6 below.

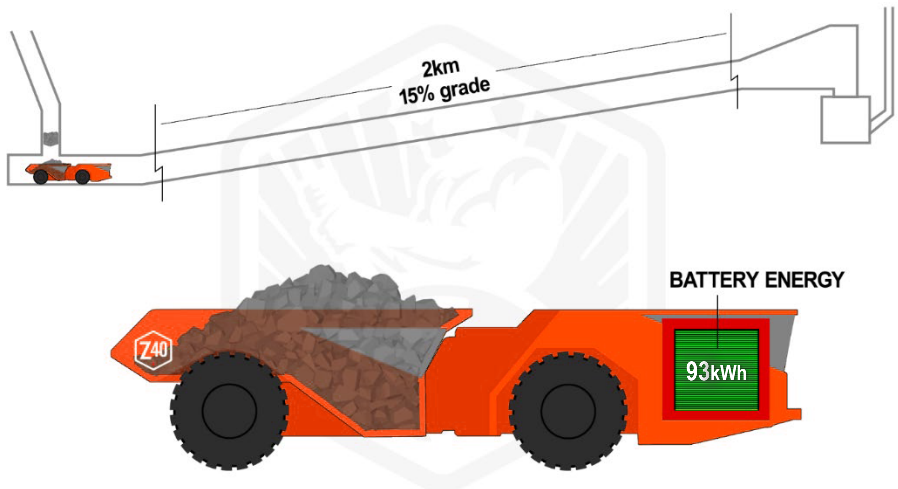

Figure 6. Z40 - Initial energy state

The base weight of the Z40 is 42 tonne. The increased weight relative to the diesel truck is due to the added battery weight. This increased weight machine requires more mechanical power to drive the truck up the ramp. The ability to recuperate the energy put into the elevation of the truck somewhat mitigates the negative impact, however. The increased weight will be evident in the energy and power flow numbers to follow. As the truck climbs the ramp, the battery energy is transferred to potential energy of the load, potential energy of the truck mass and heat in the environment. The mechanisms by which the battery energy is converted to heat is varied and not relevant to the current analysis. Similar to what was discussed for the diesel truck and captured in and captured in equation [7], the heat is the net result of all power consumed that does not move mass against gravity.

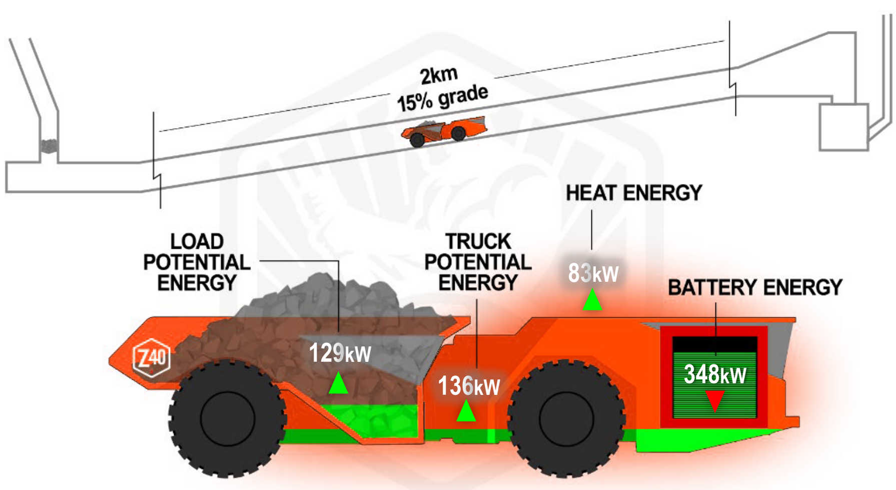

Figure 7. Z40 - Climbing loaded

At the top of the ramp we see the energy state indicated in Figure 8. The potential energy of the load is the same as for the diesel truck, but the energy of the Z40 is higher due to the increased mass. The heat energy is the result of the power loss from the climb. The battery is now fully depleted and the load energy is dumped into the load pocket where its energy state remains unchanged for the rest of the analysis. The truck is then ready to return down the ramp for another load.

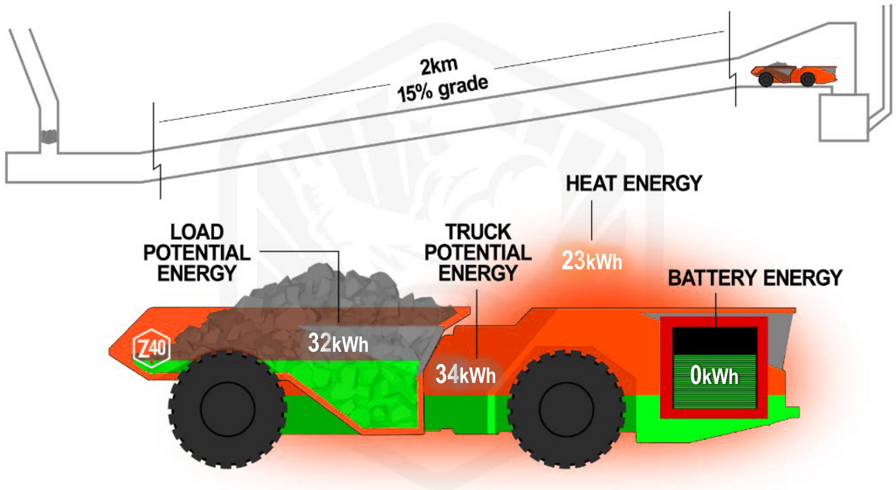

Figure 8. Z40 - Top energy state

On the return trip down the ramp, the truck potential energy is now the source of energy for the truck. Unlike in the diesel truck, the energy now has two different destinations. Some of the energy is converted to heat and a larger portion of the energy is converted to electrical energy that is used to partially recharge the battery pack. The gravitational force is converted to electrical current in the motor through the process of regenerative braking. Some of the potential energy is lost in driveline losses just as in the ascent, and some of the electrical power regenerated by the motors is used to power the steering and other auxiliaries. The losses and auxiliary load requirements end up as heat. The remaining power is used to charge the battery. These power flows from are shown in Figure 9.

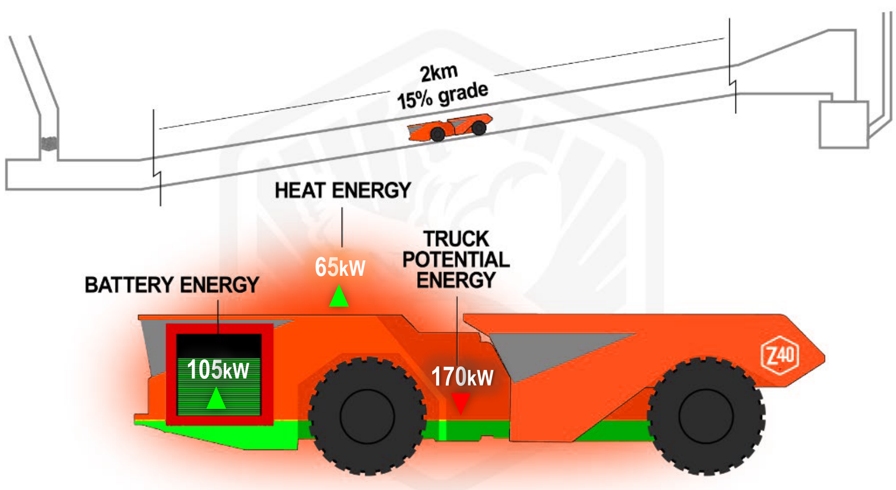

Figure 9. Z40 - Descending empty

Once the Z40 reaches the bottom of the ramp, all the truck potential energy has been drained. Of the 34 kWh potential energy at the top of the ramp, 22 kWh has been charged back to the battery pack and 12 kWh has been converted to additional heat. The final energy state is shown in Figure 10 below.

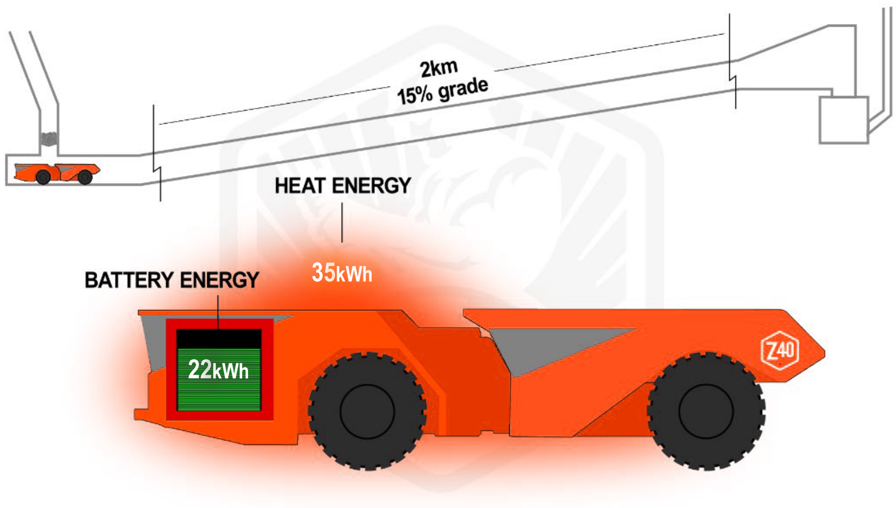

Figure 10. Z40 - End energy state

Figure 11 below shows a summary of the energy transfer in the model of the diesel truck and Z40. The total energy remains constant as the truck climbs and then descends the ramp which is consistent with the first law of thermodynamics. The yellow portion of both sub-figures indicates the potential energy of the truck mass. The mass is larger in the battery truck, which is evident in comparing the two charts. In the second half of both charts, the potential energy drops and the heat increases. The main difference between the two is that the potential energy of the Z40 is partially returned to the battery pack, which is indicated by the green area on the chart. Comparing the total heat generation for the full cycle we see that the marked reduction in heat generation during the return trip down the ramp empty results in a total ratio between BEV truck heat generation and diesel truck heat generation of 11.3%. This is just slightly over 1/9th the total heat output of a diesel truck. If regenerative braking were not considered, the comparison would indicate 18.7%, which is close to the estimations of previous authors who put the comparison at 1/5th the heat.

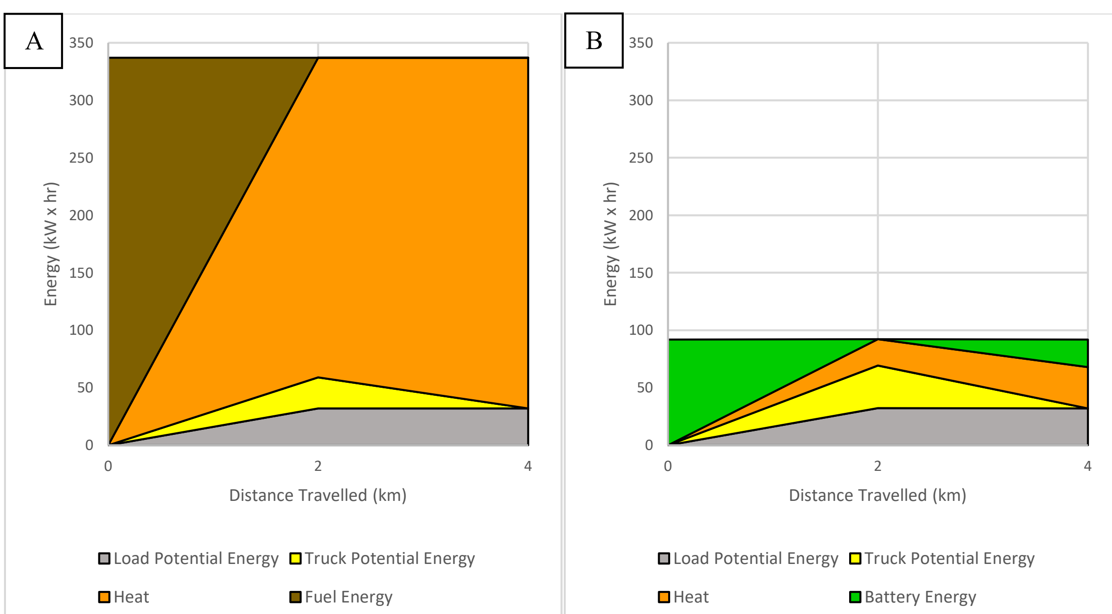

Figure 11. Energy chart

One caveat to this analysis is that the baseline diesel truck is not very efficient, and the calculated engine efficiency is on the low end of average efficiency. If we use a more efficient engine efficiency for the analysis, the fraction increases. For a 37% efficient engine, the total heat output would drop to ~237 kWh, which makes the Z40 heat output 14.6% of the diesel heat output, or closer to 1/7th.

CONCLUSION

The analysis presented steps through the different power flow states of trucks as they complete a haulage cycle. The resulting energy numbers outline both the capability of the machine and the rate of heat production in each operating mode. When comparing the power going to heat between the diesel truck in Figure 2 and the battery truck in Figure 7 you see something close to what previous authors estimated when comparing the efficiency of the powerplants. The ratio of the two powers is 27%. This number represents the combination of engine vs motor efficiency combined with improved driveline and accessory efficiency. The battery truck weighs more, which means the direct efficiency comparison would be even lower if we compared just power in vs power out for the complete truck system.

The power numbers can be used to model dynamic ventilation requirements and the instantaneous mobile heat sources in the specification and control of a mine ventilation system. The aggregate heat generation number can be used to determine the average heat load and overall cooling requirement for a mine. Engineers looking to estimate the heat output of a battery electric haultruck should start with values of 15% or less relative to a diesel equivalent. If a integer factor is desired, divide the nominal diesel equivalent power by 7, 8 or 9 depending on the perceived efficiency of the baseline diesel truck.

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