A Cost–Benefit Analysis of Electric Loaders to Reduce Diesel Emissions in Underground Hard Rock Mines

William Jacobs, Melinda R. Hodkiewicz, and Thomas Bräunl

***Abstract*—With recent developments in understanding the adverse health effects of diesel particulate matter (DPM) and growing emphasis on sustainability, zero-emission electric vehicles are becoming an increasingly common option in underground mining systems. As exposure regulations become stricter and with potential savings in the cost of ventilation, fuel, and consumables, there is also rising economic incentive to consider alternatives to diesel machinery. As a result, the diesel–electric debate is fundamental to any underground mining company's triple bottom line. A cost–benefit analysis for electric load haul dump units (eLHDs) was conducted in the context of Western Australian underground hard rock mines. This included a review of the issues affecting the diesel–electric debate and the development of a parametric life-cycle-cost model. The results indicate that eLHDs are not yet a universal solution to all underground mining systems. eLHDs can offer lower operating costs and do contribute many qualitative benefits, particularly with respect to reduced exposure to DPM. However, they also have several drawbacks, primarily associated with trailing cable management. Nevertheless, with a suitable mine design, eLHDs are a viable option and could provide a pathway for zero-emission electric machinery in the Australian mining industry. *Preamble*—Western Australia is one of the world's leading mineral provinces. In the 2012–2013 financial year, Western Australia's mineral and petroleum sales totaled A$102 billion, representing some 42% of Australia's total merchandise exports. As such, changes to the Western Australian mining industry has national and international economic implications.**

***Index Terms*—Cost, diesel, electric, health, loader, mining, underground.**

I. Introduction

DIESEL particulate matter (DPM) is emitted by diesel engines due to incomplete combustion and impurities in the fuel [2]. There have recently been major developments in understanding the health risks associated with DPM. In June 2012, the World Health Organization declared DPM a Group 1 carcinogen. This classification was based on studies by the International Agency for Research on Cancer (IARC), which concluded that DPM exposure is linked to an increased risk of developing lung cancer [3]. Intuitively, these health issues are more immediate underground than in an open pit environment, and a report by Bugarski *et al.* [4] stated that underground miners are exposed to the highest concentrations of DPM of all occupations.

In Western Australian underground mines, while regulations have been introduced in response to IARC's recent findings, there are no statutory limits for DPM exposure. Furthermore, exposure regulations (0.1 and 0.07 mg/m^3 of elemental carbon over 8 and 12 h, respectively) are the total-weight-average limits, which do not account for brief periods of intense exposure [5].

While a number of alternative fuel sources have been explored for underground mining vehicles (including fuel cell and natural gas), currently, the most available alternative is electricity. Due in part to fleet numbers and operation hours, the most common underground electric vehicles (EVs) are load haul dump units (LHDs). LHDs are typically diesel, however, electric LHDs (eLHDs) are becoming increasingly common [6]. These vehicles could theoretically be powered by one of three electric options: batteries, overhead power lines/rails, or (most commonly) tethered trailing cables.

Batteries offer the highest flexibility of the three options; however, battery-powered vehicles are far heavier and must be regularly recharged. In a study by Greenhill and Knights [7], LHDs required 1.5–2 tonnes of batteries, and this only allowed 2–2.5 h of working time. Recharge time is estimated at 2 h, resulting in an undesirable vehicle availability of around 50%. Trolley mechanisms using overhead power lines may be feasible for haul trucks where routes remain constant for an extended period of time but are impractical for LHDs, which require a high degree of maneuverability. An umbilical trailing cable plugged into the electrical infrastructure of the mine is currently the most viable way to power eLHDs.

eLHDs are zero-emission vehicles and produce less noise, vibration, and heat [8], providing better working conditions for employees. There is also an economic incentive to consider eLHDs, with potential savings in ventilation, fuel, consumables, regulation checks, and maintenance [6], [9]. However, the limitations imposed by trailing cables present several drawbacks [6]. These include reduced mobility, versatility, cable faults, and relocation issues.

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The objective of this study is to conduct a cost–benefit analysis of eLHDs via a literature review and a life cycle cost (LCC) model. Ultimately, any decision concerning the feasibility of eLHDs must consider a range of decision criteria, including economic, environmental, social, and logistical considerations. Due to the lack of published diesel–electric LHD comparative studies, this paper fills a gap in the current literature and provides a springboard for discussion.

II. Literature Review

A. Health

Perhaps the most documented motive to seek alternatives to diesel is health. A report by Schneider and Hill [10] estimated that DPM shortens the lives of nearly 21 000 people in the U.S. every year. Hedges *et al.* [11] report that short-term exposure to DPM can hamper the respiratory and immune systems, particularly for those with asthma or allergies.

A number of recent epidemiological studies specific to the underground mining industry [12], [13] have demonstrated an increased risk of lung cancer due to DPM exposure. These reports have contributed to the World Health Organization declaring DPM a Group 1 carcinogen.

Furthermore, a decision made in the Canadian Superior Court in January 2013 has set a legal precedent for DPM exposure compensation claims. Having passed through Québec's Occupational Health and Safety Commission as well as the Employment Injury Commission, the court recognized the lung cancer of now deceased mine electrician Claude Fortin as an occupational disease. The family is now eligible to receive compensation, despite there being no evidence to prove that the mine had exceeded exposure regulations [14].

In addition to the carcinogenic exhaust, another health issue associated with diesel vehicles is noise level [15]. The average noise level for EVs is 85 dB, in comparison to 105 dB for diesel vehicles [16].

B. Ventilation

A second driving force for the replacement of diesel machinery in underground mines is ventilation costs. De la Vergne [2] states that ventilation typically accounts for over one-third of the electrical operating costs of an underground mine, while Paraszczak *et al.* [8] suggest this figure is up to 40%. Both Halim and Kerai [17] and Paraszczak *et al.* [8] conclude that use of zero-emission EVs, with approximately one-third of the heat emission of their diesel counterparts, will reduce ventilation requirements. Furthermore, Paraszczak *et al.* [8] forecast that, as mines get deeper and hotter and emission regulations get stricter, ventilation costs will continue to rise unless alternative technology is implemented.

Western Australia's Mines Safety and Inspection Regulations 1995 (hereafter, WAMSIR 1995 [18]) stipulate a ventilation requirement of 0.05 m^3/s per kilowatt of diesel engine power if the maximum exhaust gas emissions of the engine in a diesel unit contain less than 1000 ppm of nitrous oxides and less than 1500 ppm of carbon monoxide. If emissions are above these thresholds, then the requirement is raised to 0.06 m^3/s/kW.

TABLE I
Diesel Fume Dilution Requirements Around the World (Adapted From [30])

Location	Diesel Airflow Requirement (m^3/s/kW)
Western Australia	0.05
Queensland	None
Ontario, Canada	0.06
United Kingdom	None
United States	0.032 - 0.094
Chile	0.063
South Africa	None
Indonesia	0.067

Table I shows diesel fume dilution rates around the world. WAMSIR 1995 [18] also specifies a minimum flow rate of 2.5 m^3/s where diesel machinery is operated. However, the only regulation in place for EVs is that a minimum air velocity of 0.25 m/s is to be maintained, which is independent of motor size.

A study by Halim and Kerai [17] aimed to quantify ventilation standards for EVs. While no ventilation is required for the dilution of fumes or DPM, it is still necessary for temperature control and to provide oxygen to employees. The investigation determined that, for deep mines, the ventilation requirement for EVs should be 0.04 m^3/s/kW—a 20% reduction. For shallow mines, the EV requirement was advised to be 0.025–0.037 m^3/s/kW, dependent upon thermal conditions.

C. Trailing Cables and Mine Design

The major source of eLHD issues is the umbilical trailing cable. Drawbacks include restricted movement, limited haul range, cable wear, and interference with autonomous light barriers [6]. Chadwick [19] also cites cable reel issues and related expenses as shortcomings of electric equipment but suggests that these problems could be alleviated by proper mine design.

Moving eLHDs between production areas can be a time-consuming and costly exercise. If junction boxes are not available along the way, Paraszczak *et al.* [8] suggest that electric loaders must tow a portable diesel generator. The other option is to tow the eLHD by one of its diesel counterparts. This then affects the utilization of each machine, in turn resulting in lost revenue. Relocation delays and costs can be less critical in mine layouts where haulage is performed along a similar path for an extended period of time.

D. Previous Comparative Studies

Previous studies were difficult to obtain, as only a few have been published. The comparative study by Paraszczak *et al.* [8] is predominantly a literature review, with no actual case study to support the observations. The main data sources for the Paraszczak *et al.* [8] paper are from InfoMine, as well as Sandvik product specifications retrieved online. The paper concludes that electric loaders have multiple advantages over their diesel counterparts, including the lack of exhaust gases,

TABLE II
AVAILABILITY, UTILIZATION, AND MAINTENANCE COMPARISON (SOURCE: [6])

Drive	Data sets	Mean availability (%)	Mean UoA[1] (%)	Mean utilisation (%)	MTBF (hrs)	MTTR (mins)
Diesel	2	91.94	66.88	61.46	32.76	184
Electric	6	88.29	77.18	68.13	21.95	167

[1]UoA: use of availability

lower heat emission, possible ventilation savings, and superior energy efficiency. However, the authors also suggest that these tethered machines cannot compete with the versatility of diesels and advise that block or sublevel caving operations are the most suitable mining methods for eLHDs.

Paterson and Knights [6] completed a study into the management of eLHD trailing cables. Like Paraszczak *et al.* [8], Paterson and Knights [6] conclude that, due to limitations imposed by the trailing cables, electric loaders are not suitable to all mining scenarios. They propose that block and panel caving operations and centralized long life extraction levels are most suitable, with offset herringbone or herringbone level layouts. With this layout, eLHDs are always facing in the same direction, and the power feed is located at one end of the panel.

The Paterson and Knights [6] paper references data sets of six eLHDs and two diesel LHDs, taken over 414 days at Rio Tinto's Northparkes Mine. Availability, utilization, and maintenance data are shown in Table II. Note that MTBF and MTTR are abbreviations for "mean time between failure" and "mean time to repair," respectively.

Electric loaders had less scheduled maintenance, and the mean time to repair was lower, but they required more frequent unscheduled maintenance compared with diesel LHDs. An average of 1660 incidents were recorded per eLHD, compared to 1415 per diesel. Overall, this resulted in approximately 50% more downtime for eLHDs and, therefore, a lower availability rate. A major contributor was that 15% of eLHD maintenance was due to trailing cable issues and electrical faults, in comparison to 6% for diesel loaders.

III. METHOD

A. LCC Model Development

Standards Australia's *Life cycle costing—An application guide* [20] was used to structure the LCC model. The model used only includes the acquisition and operation phases of the asset life cycle and assumes that there will be no disposal within the ten-year period considered.

A cost breakdown structure was developed, and costs were assigned to individual elements. Fig. 1 shows a simplified model schematic. Since this is a comparative study, elements that are constant for both diesel and electric loaders, for example, operating labor, are not included. A parametric costing method is employed. This uses parameters and variables to develop cost element relationships in the form of equations [20].

Cost elements (inputs) are developed for daily operating costs, usage hours, and ventilation savings; these are summarized in Table III and described in the following section. All input cost elements are specified in real costs,[1] and the sum of future costs is determined using a net profit cost (NPC) approach. The model generates results for the base case assuming a specific LHD fleet size and diesel–electric configuration with which alternative fleet configurations are compared. Sensitivity analysis is performed to gauge the influence of each cost element.

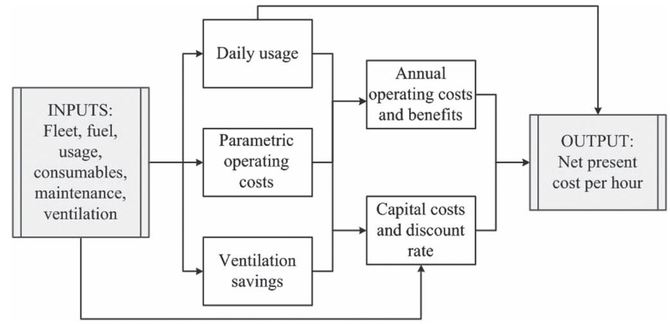

Fig. 1. Basic cost model configuration.

TABLE III
LIST OF BASE COST MODEL INPUTS

Input	Units	Input Values		
		Diesel: LH514	Electric: LH514E	General: Both
Fleet:				
Fleet number	-	4	4	-
Unit capital	$M/unit	1	1.2	-
Discount rate	%	-	-	9
Fuel:				
Fuel cost	$/L	1.13	-	-
Fuel consump.	L/hr	40	-	-
Power	kW	256	180	-
Electricity cost	$/kWh	-	-	0.2
Usage:				
Availability	%	85	80	-
Use of availability	%	70	70	-
Consumables:				
Lubricants	$/hr/unit	8	5	-
Tyres	$/hr/unit	-	-	15
Filters	$/hr/unit	8	-	-
Maintenance:				
Machine	$/hr/unit	70	50	-
Cable	$/hr/unit	-	30	-
Labour	$/hr/unit	20	25	
Ventilation:				
Requirement	m^3/s/kW	0.05	0.03	-
Primary power	kW	-	-	500
No. primary	-	-	-	2
Flow rate	m^3/s	-	-	200
Aux adjustment	-	-	-	2
Operating hrs	hr/day	-	-	23.5

B. Justification of Inputs

1) Estimation Techniques: Two editions of the Australasian Institute of Mining and Metallurgy (AUSIMM) *Cost Estimation Handbook for the Australian Mining Industry* [21], [22] have been used to make estimates. The older edition of the Cost

[1]2013 Australian dollars (A$)—at the time of writing, A$1 bought around US$0.94.

Estimation Handbook had more content with regard to LHD units and so has been used more prominently. Values used from the 1993 edition of the *Cost Estimation Handbook* have been adjusted to account for inflation using the Reserve Bank of Australia retrospective Inflation Calculator [23].

2) Fleet Number: Fleet size is dependent on the size of the mine and the production targets. Fleets can vary from as little as one or two loaders to dozens (according to Australia's Mining Monthly 2011 Underground Mining Survey [24], Mount Isa Copper Mine has 25 loaders). The default fleet number was selected as eight loaders: four diesels and four electrics.

For this study, one size of LHD is considered. This is the large capacity LHD ($\sim$15-tonne payload), which is the most common size of LHD in Australian hard rock mining, according to Australia's Mining Monthly [24]. The Sandvik LH514 and LH514E models were chosen as a suitable pair of similar diesel and electric machines.

3) Unit Capital Cost: According to Moore [16], eLHDs have a capital cost approximately 20% higher than a similar diesel unit. Paraszczak *et al.* [8] indicate that an electric loader with a bucket capacity of 1.5 m^3 costs approximately 30% more than an identical diesel machine. However, for bigger loaders, this difference is between 20% and 25%. AUSIMM [22] suggests that a 13–15-tonne capacity diesel LHD will cost around $1 million in real 2010 prices. This is supported by the data from InfoMine (cited in [25]), which indicates that a reasonable price for a large diesel loader is around $1–1.1 million and that for an electric model is $1.2–1.3 million. The default values were selected as $1 million and $1.2 million, respectively.

4) Fuel Price: Based on the Australian Institute of Petroleum's weekly diesel report (week ending October 6, 2013), the terminal gate price or wholesale price for diesel was around $1.45/L at the time of writing [26]. This is prior to diesel fuel rebates offered by the Australian government. As of July 1, 2013, these rebates were cut by 6 c/L in the mining industry to around 32 c/L [27]. This gives a revised fuel price of $1.13/L.

5) Fuel Consumption: Based on AUSIMM [21], a realistic diesel consumption rate for a large LHD is 40 L/h.

6) Engine/Motor Power: Diesel engine and electric motor power ratings were sourced from Sandvik product specifications available online. These were 256 kW for LH514 and 180 kW (total installed power) for LH514E [28], [29].

7) Electricity Price: Electricity price is a fluctuating and complex variable that is dependent on a number of factors, including energy provider, peak/off-peak rates, and demand. Consequently, a large price range exists for grid supply, typically $0.15–0.25/kWh. The default value was set at $0.2/kWh. Electricity generation is considered later in the *Results* section.

Australia's carbon tax was not considered, due to the likelihood of it being abolished with the recent election of Abbott's Liberal government. Additionally, the number of free carbon units allocated by the government varies between mines and is difficult to predict.

8) Availability and Utilization: With regard to availability, the Northparkes Mines data cited by Paterson and Knights [6] presented values for availability and use of availability of 92% and 67% for diesel LHDs and 88% and 67% for eLHDs, respectively. Other industry sources listed availability and use of availability of a diesel LHD as 72% and 62%, respectively.

AUSIMM [22] offers some typical availability rates with respect to condition, directed toward open cut machinery. Assuming that the availability of an LHD would be similar to a front-end loader and that the unit is new, a suitable availability range is around 84%–88%. Ultimately, the default for diesel availability was evaluated as 85% and 80% for EVs.

The use of availability is site specific and depends on operating philosophy, roster, management efficiency, shift changeover, and fleet size, among other things [22]. For consistency, a value of 70% was chosen for each drive system. While diesel machines can offer higher operational flexibility and therefore may be selected for a wider range of tasks, the argument could also be made that eLHDs could be favorable due to their potential lower operating costs.

9) Consumable Cost: AUSIMM [22] notes that consumable costs are highly dependent on LHD size and working conditions. Hourly costs per unit (derived from [21]) for lubricants were deemed to be $8/h for diesel and $5/h for electric. The discrepancy here is due to the fact that engine and transmission lubricants are not required for electric models; however, lubrication of hydraulic systems and axles is still necessary.

With respect to filters, a base rate of $8/h/unit was decided upon for basic engine filters.

LHD tire life is heavily dependent upon work conditions and road surface and typically lies in the range of 400–1400 h, with an average of 800 h [21].

Tires were estimated at $15/h/unit in each case.

It must be noted that consumable and maintenance costs are specified per usage hour (obtained from utilization rates and typically around 14 h per day).

10) Maintenance Cost: Moore [16] notes that electric loaders are generally considered to be cheaper to maintain. Paraszczak *et al.* [8] propose that electric motors are easier to maintain and require less qualified personnel and less sophisticated tooling. However, Paraszczak *et al.* [8] also identify that these machines require additional maintenance with regard to trailing cables and reels, which are exposed to frequent damage and are expensive to replace.

Using AUSIMM's *Cost Estimation Handbook* [21], it is estimated that diesel machines incur a maintenance cost of around $70/h. This includes parts such as bucket lips and linings, hydraulic hoses and cylinders, seals, valves, pins, undercarriage components, wheel bearings, brakes, bodywork, transmission, and engine components. Excluding trailing cables, electrics are slightly cheaper, at around $50/h. This is due to savings in engine and transmission maintenance.

It must be noted that these values are purely for materials, so the labor costs of fitters, mechanics, or automotive electricians performing the maintenance must also be accounted for. AUSIMM [21] estimates this is around 40%–50% of the operating labor. Operating labor has not been included in this model since it is assumed that there will be no difference between drive systems. For the purpose of estimating maintenance labor, AUSIMM [21] quotes the average drill jumbo operator base salary in 2009 Australian dollars as $160 000. Assuming that an LHD operator will cost a mining company around

\$200 000 in total over the course of a year, this breaks down to approximately \$40–50 per operating hour per unit. Hence, one could estimate the maintenance labor costs at around \$20 per operating hour per unit.

The Northparkes Mines case study presented in the literature review [6] concluded that eLHDs had slightly shorter maintenance times but also need maintenance more frequently. This resulted in a discrepancy in availabilities that suggested around 50% more downtime for eLHDs.

In summary, it was decided that eLHDs are more expensive to maintain, despite popular belief. InfoMine USA data referenced by Paraszczak *et al.* [8] estimate maintenance costs of electric LHDs as being approximately 20% higher than that for diesel machines. In order to reflect this, maintenance labor costs for eLHDs were set at \$25 per operating hour per unit, while diesels were set at the previously derived \$20 per operating hour per unit. Also, an estimate of \$30/h was factored in for trailing cable maintenance. This is highly dependent on the surface conditions, and preventative measures (described in the *Discussion*) could be taken to minimize this cost. In total, the default values summed to \$90/h for labor and parts for diesels and \$105/h (around 17% higher) for eLHDs.

11) Ventilation Cost Modeling and Specifications: Due to the cubic relationship between air power and flow rate [30], it was difficult to break down ventilation into cost per unit, as was done with other parameters. The ventilation constituent of the cost model was instead configured around a ventilation savings approach, taking ventilation costs for diesel machines as zero.

The ventilation requirement for diesel machines was taken from WAMSIR 1995 [18] as 0.05 $m^3/s/kW$. The study by Halim and Kerai [17] proposed EV ventilation requirements of 0.04 $m^3/s/kW$ for deep mines and 0.025–0.037 $m^3/s/kW$ for shallow mines, depending on thermal conditions. The default value was chosen to be 0.03 $m^3/s/kW$.

The inputs of primary fan power, number of primary fans, and the auxiliary fan adjustment factor are multiplied together to obtain the total power ventilation system. The auxiliary factor accounts for secondary systems needed to boost airflow and supply air to working faces of blind headings and sublevels in the mine. Typical mining industry ventilation system specifications were assumed. These were two primary fans rated at 500 kW, an auxiliary factor of 2, and a mine flow rate of 200 m^3/s. A ventilation system operating time of 23.5 h was considered. Ventilation systems are generally run close to 24 h per day, and the small discrepancy was to account for downtime due to closures or fan maintenance.

C. Output Metrics

Since the output of the model is provided in the form of an NPC per unit after ten years (denoted NPC10), considerations regarding the operating hours of the different machines also had to be made. Intuitively, if a unit is operating for longer, it will incur higher operating costs. Without accounting for operating hours, this would then penalize a machine with a higher utilization. Consequently, the output of the cost model was decided to be a net present cost calculated over ten years using a discount rate of 9%, divided by the operating hours over that period.

Note: Hereafter, any costs expressed as "hourly costs" refer to the output described earlier.

TABLE IV
BASE CASE RESULTS

Base Case	Diesel	Electric
Hourly cost per unit (\$/hr)	125.8	85.0
Total hourly cost (\$/hr)	503.3	339.9

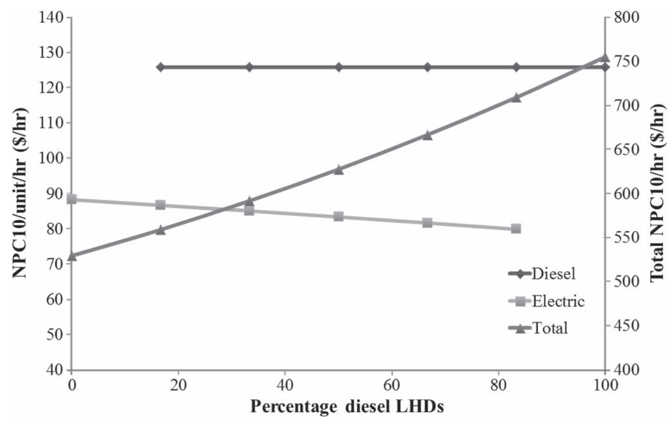

Fig. 2. Hourly cost for combinations of six LHDs (total cost uses right axis).

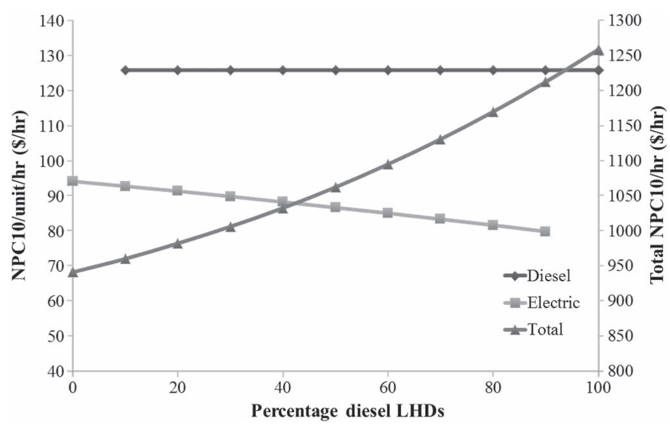

Fig. 3. Hourly cost for combinations of ten LHDs (total cost uses right axis).

IV. RESULTS

A. Base Case Results

For the default inputs, the model yielded outputs displayed in Table IV. It can be seen that, for the base case, the hourly cost per electric loader is around 30% less than that per diesel loader.

B. Effect of Fleet Number

Figs. 2 and 3 show diesel and electric LHD hourly costs per unit plotted on the left vertical axis and total hourly costs on the right for total fleet numbers of 6 and 10, respectively. It is evident that as the proportion of diesel machines increases, hourly costs per diesel unit remain the same, while hourly costs per electric unit actually decrease.

This decrease is due to the ventilation savings aspect. The eLHD hourly cost is dependent upon the electric fleet number. As the number of eLHDs increases, so too does the hourly cost per unit, which can be interpreted as more units having to "share" ventilation savings. It is a nonlinear relationship, and as the number of eLHDs increases, the change in hourly cost decreases.

While this may seem counterintuitive, consider the total hourly costs, also displayed in Figs. 2 and 3. These plots were obtained by multiplying diesel and electric costs per unit by their respective number of vehicles and then summing the total. The graphs illustrate that, as the proportion of diesel units increases, so too does the total hourly cost. While eLHD hourly cost per unit does rise with an increased number of electric units, for realistic fleet numbers (less than 30), this never exceeds the hourly cost per diesel, so total costs rise with a higher percentage of diesel loaders.

C. Sensitivity Analysis

A sensitivity analysis was then performed. The outcomes are summarized as follows.

1) The most significant sensitivities are maintenance and ventilation.
2) The 10% increases in maintenance costs caused the total costs to rise by around $50/h.
3) The 10% increases in ventilation power caused the total costs to *decrease* by around $17/h.
4) Increases in the base electricity price of 1 c/kWh *decreased* total costs by around $4/h.
5) For every $0.1/L increase in diesel fuel price, hourly cost per diesel unit rose by around $2.6/h/unit.
6) If the EV ventilation requirement can be lowered down to 0.01 m^3/s/kW, this would bring significant savings of approximately $65/h.

This last point is made based on the plausibility that ventilation requirements for EVs may be significantly lower than the default value of 0.03 m^3/s/kW. This is due to EVs emitting no fumes or DPM, demonstrating significantly lower heat emission and needing no oxygen for combustion. The default value was derived from a paper by Halim and Kerai [17]; however, no other studies were found that have attempted to quantify EV ventilation requirements.

D. Electricity Price and Generation

Although the sensitivity analysis did not indicate that small changes in this parameter were particularly influential on the output, electricity prices are prone to fluctuations. The base case considered grid electricity; however, many Australian mines are off the grid, so the price of electricity generation should also be taken into account.

A number of options are available for electricity generation. Diesel generators typically cost around $0.28–0.32/kWh to run, while natural gas can be down around $0.18/kWh. Solar is a new alternative for electricity generation on mine sites, with Lazenby [31] and Parkinson [32] agreeing that this could offer reduced costs of approximately $0.16–0.17/kWh. Wind power is another potential option at around $0.14/kWh [31].

The price of electricity has two effects on overall costs: the cost to power eLHDs and the cost to power the ventilation system. Similar to the effect of increasing the power of the ventilation system, increasing the price of electricity also enables higher potential ventilation savings. It was found that these ventilation savings far outweigh the additional cost of powering the electric units, due to the power of the ventilation system (typically several thousand kilowatts) being much larger than the power of the loaders (each around 180 kW). Therefore, as electricity prices increase, the effective hourly cost to operate an eLHD drops. For the default settings, every $0.01 that the electricity price increased was found to decrease total costs by around $4/h.

E. Other Alternatives (Outside Scope)

It should be mentioned that diesel particulate filters and biodiesel options were also briefly studied. These were modeled with reduced ventilation requirements due to reduced DPM emissions, as well as changes to such parameters as consumption, maintenance labor, consumable costs, and availability. Both alternatives were found to potentially offer cost savings for diesel vehicles, although neither could offer savings as large as EVs. These results will not be discussed further as they were outside the scope of the study and were not modeled in sufficient depth.

V. Discussion

A. Findings From the LCC Model

The base case results are consistent with the initial expectation and the general consensus from the literature that electric loaders can offer lower operating costs. The primary cause of this was found to be the potential savings in ventilation. If ventilation savings were not included in the model, the hourly cost per unit for eLHDs became $128/h/unit, $2/h/unit more than diesel loaders. This large effect of ventilation savings stems from the cubic relationship between air power and volume flow rate. In theory, if the flow rate can be reduced by 20%, this will pass on power (and therefore cost) savings of around 50%.

Electric loaders were modeled to be 20% more expensive to acquire and around 17% more expensive to maintain yet were still found to be around 30% cheaper to operate overall. The other cost elements which served to offset these added costs were savings in energy cost and consumables. These were respectively around 20% and 35% less expensive than the corresponding diesel values.

With respect to fleet configuration, total hourly costs were always greater with a higher proportion of diesel units.

The sensitivity analysis concluded that changes in maintenance inputs have the most influence on the output, with 10% rises equating to around $50 increases in total hourly costs. For example, if trailing cable maintenance costs blow out to $80 per operating hour and if eLHD maintenance labor rises to $40 per operating hour, eLHDs then become the more expensive option at around \$128 per unit per hour. In this light, mine design and surface conditions are key considerations to the feasibility of eLHDs.

Ventilation power was the other significant sensitivity, and changes of 10% were observed to change total hourly costs by around \$17/h. Due to increased possible ventilation savings, raising the ventilation system power had the effect of lowering hourly costs. Lowering EV ventilation requirements down to 0.01 m^3/s/kW from the assumed value of 0.03 m^3/s/kW brought substantial savings of approximately \$65 per hour to total hourly costs. This shows that if power-dependent ventilation requirements are introduced for EVs, how low this value is set will have major implications on the economic feasibility of electric machinery.

Syed and Penney for the Bureau of Resources and Energy Economics [33] as well as data from the U.S. Energy Information Administration [34] forecast relatively stable oil and diesel prices in the short term. Despite this, analyzing the effect of diesel fuel price was deemed necessary due to the uncertain future of world politics, diesel rebates, and carbon taxing schemes. Ultimately, this was found to be relatively insignificant in comparison to other parameters, as increases of 10 c/L in diesel price caused rises in diesel vehicle hourly costs of around \$2.6 per unit, representing a rise of just 2%.

As far as electricity prices are concerned, increases of 1 c/kWh actually decreased total costs by around \$4/h. This is a result of the savings in ventilation offsetting the small additional costs of powering the loaders, due to the ventilation system being much more powerful than the loaders themselves.

It should be noted that, when eLHD hourly costs are said to decrease due to higher potential ventilation savings, this is in *relative* terms, taking diesel unit ventilation costs as zero. Rises in electricity price or ventilation requirements do not benefit a mining company's bottom line; however, these cases will make electric units more economically attractive in comparison to diesel units. In other words, higher ventilation costs will still come at a greater *overall* operating cost to the mining company; however, the *relative* cost of electric loaders in comparison to diesel loaders will decrease.

B. Limitations of the Model

The first limitation of the LCC model is the lack of available field data for estimating model inputs. Maintenance and consumable cost elements were largely based on figures from AUSIMM's first edition of the *Cost Estimation Handbook*, published back in 1993. Maintenance, which proved to be such an important factor in the LCC model, is also dependent on a range of factors, including operating conditions, mining methods, mine design, and management strategies, so estimating generic values is difficult.

Ventilation was modeled in several different ways throughout the course of the model formulation, and while the final "savings" method was superior to the other methods trialled, there may exist better approaches. The model calculates savings based on changing volume flow requirements with respect to a typical ventilation setup. For this to have any accuracy when applied to an existing mine, these specifications should be set to those of the mine in question, which may not be known. The model requires the knowledge of the airflow rate when all loaders are diesel and assumes that, at this initial condition, the ventilation system is running at 100% and is providing the exact required flow rate. In reality, ventilation systems are likely to be oversized, to allow for a safety factor.

Another limitation is the assumption that changes to ventilation requirements are possible. This was an assumption necessary to make in this analysis since it is the main economic driving force behind choosing electrical equipment in underground mines. While determining an appropriate ventilation requirement for EVs may require further studies, this will certainly be significantly lower than the current diesel requirement of 0.05 m^3/s/kW.

The other assumption made was that variable speed drives are installed for primary fans. Most primary fans are set to run at 0% or 100% (direct online), and in order to fine-tune the output flow rate, variable speed drives would be required. These drives come at a significant expense of around \$150 000, which represents around 10%–15% of the capital cost of a primary fan.

There were also a number of other possible costs which were difficult to factor in. The ongoing cost due to emission inspections of diesel machinery may be significant in years to come. Similarly, infringement fines from breaches of exposure limits or ventilation regulations may represent a significant cost. The current WAMSIR 1995 penalty for a ventilation infringement is \$50 000 for a first offense and \$62 500 for subsequent offenses [18].

The cost relating to the relocation of electric loaders between haulage routes was not included into the model due to its heavy dependence on the specific mining task, mine design, and management. There are also several options for transporting the eLHDs, including towing by diesel units and the use of diesel generator sets. This will impact availability and, in turn, productivity (see the following section). According to Moore [16], for a large site where frequent relocation is required, a cost of 10%–20% of the total operating costs should be factored in. Although this is a fairly vague estimate, if we consider this on top of the base hourly cost per eLHD of \$85, we get around \$100, which is still significantly lower than the diesel hourly cost per unit.

C. Effect of Productivity

Due to the large revenues possible in the mining industry, productivity is perhaps the most important economic consideration. Productivity is a function of cycle time, which is, in turn, dependent upon a huge number of factors including load/dump times, bucket capacity, haul distance, speed, road grade, surface conditions, and mine layout.

A typical LHD productivity can considered to be several hundred tonnes per hour. Depending on the metal, this ore could be worth hundreds or thousands of dollars per tonne, so each loader may mine anywhere between tens and hundreds of thousands of dollars worth of ore each hour. This demonstrates how very small changes in availability or productivity can offset very large changes in operating costs.

There is no consensus among academics on the relative production rates of diesel and electric loaders. While the operational flexibility of diesels generally renders them more productive, Miller [9] points out that constant regulation checks can hamper productivity. Also, according to Chadwick [19] and Paraszczak *et al.* [8], the constant torque (including high torque at low speeds), quicker response to the load, and better overload capacity of electric motors can lead to higher productivity rates.

Another point raised by Paraszczak *et al.* [8] is that the more comfortable and safer working environments associated with eLHDs can result in higher work efficiency. However, they concede that diesel loaders are 30%–50% faster and can have loading/dumping times that are a few seconds shorter. This can result in shorter cycle times and therefore increase productivity. Comparing productivity rates is certainly an area which requires further research.

D. Other Decision Criteria

Ultimately, a range of decision criteria, not just economics, must inform the decision on the feasibility of electric loaders. Social and environmental considerations are in favor of electric loaders, due to the lack of gaseous and particulate emissions. Combined with less noise and heat and improved visibility, these attributes can provide a better safer working environment.

Energy infrastructure is another consideration. Underground mines already have an electricity supply network for equipment such as jumbos and production drills, which are maneuvered using diesel engines but are powered electrically during operation. However, depending on the number of electric loaders, electrical infrastructure may need to be upgraded. Due to the high power demand of eLHDs, Paterson and Knights [6] suggest a maximum of four units per substation. Additional infrastructure may include underground power lines, substations, transformers, and sockets. Backup generators may also be required to ensure that work could continue in the event of a power failure. However, if a mine was to go fully electric, savings could then be made on diesel infrastructure such as storage tanks, refueling stations, and piping.

In terms of logistical considerations, electric models prove to be inferior. Electric units must either be fitted with a small diesel generator or must be towed by a diesel unit in order to move between haulage routes. This affects the utilization rates of the loaders and can come at a significant cost to the mining company. Relocation costs, combined with cable damage and restricted movement, mean that certain mining methods and layouts are much more preferable for electric loaders. Chadwick [19] suggests that this necessity to employ specific mine plans for effective use is one reason for the reluctance to embrace underground electrical equipment.

VI. Conclusion and Future Work

eLHDs have many advantages over their diesel counterparts in underground hard rock mining. At the surface, the most obviously appealing feature of these vehicles may be their lack of emissions, particularly with the recent developments in the adverse health effects of DPM. However, many academics have suggested that electric models can also deliver reduced operating costs.

The LCC model confirmed this hypothesis. For the default inputs and a realistic fleet size, electric loaders had lower operating costs relative to diesel loaders, and hence, a higher percentage of diesel units resulted in higher operating costs. Mines with large ventilation requirements make electric alternatives more economically viable, due to increased potential ventilation savings. This is also the case for higher base electricity prices, due to either rising grid prices or the higher costs associated with diesel-powered generators.

Maintenance and ventilation were found to be the key influences on operating costs. To this end, if potential ventilation savings by eLHDs were ignored, then these units actually became the slightly more expensive option. This was also the case if default cable maintenance costs were allowed to triple. The logistical issues imposed by the trailing cables of electric loaders are the main downfall of these units.

Consequently, eLHDs are not a universal solution to all underground mining systems. For eLHDs to be successfully implemented, trailing cable damage and relocation should be minimized. Less abrasive surfaces, such as concrete, are preferable, and straight haul routes may prevent damage from corners. Constant haul routes for extended time periods are also beneficial, by minimizing relocation costs. Paterson and Knights [6] suggest that block and panel caving operations and centralized long life extraction levels are most suitable, with offset herringbone or herringbone level layouts. The need to tailor mine design around electric loaders may mean that the widespread introduction of these vehicles is more valid to new "greenfield" mining projects, rather than existing "brownfield" mines.

Future comparative productivity trials are vital in definitively determining the economic feasibility of electric loaders. More studies aimed at quantifying operating costs of loaders and ventilation requirements of EVs are also necessary, due to the lack of published work in these areas. In a similar manner to the way in which this report was compiled, the feasibility of other machinery such as electric haul trucks could be analyzed, with the prospect of one day designing a fully electric mine site. Further research is warranted in improving the design of trailing cables since these are the source of most of the shortcomings of eLHDs. At the same time, the design of battery-powered underground mining vehicles should continue to be developed and refined. The final recommendation is that ventilation requirements need to be revised, and there should be a clear distinction made between dilution rates for exhaust gases and those for DPM. The Mining Safety and Health Administration model implemented in the United States is a good example of how this could be introduced.

In summary, the main objective of this study, which was to conduct a cost–benefit analysis of eLHDs in Western Australian underground mines, has been successful. There are limitations to the work, mostly stemming from the shortage of previous studies, the way in which ventilation was modeled, and the lack of knowledge on relative productivity rates. However, this report can serve as a base for future work and provides a comparative study between electric and diesel LHDs in underground hard rock mines.

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