<u>Electric LHDs in Underground Hard Rock Mining:</u>
<u>A Cost/Benefit Analysis</u>

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Project Summary

With recent developments in the adverse health effects of diesel particulate matter 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 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.

Diesel fueled load haul dump units (LHDs) operate in fleets underground for long hours, and as such are of particular significance. The main objective of this study is to conduct a cost/benefit analysis of the implementation of electric LHDs (eLHDs) in Western Australian underground hard rock mines. This was achieved through a comprehensive review of the issues affecting the diesel/electric LHD debate, as well as through the development of a parametric life cycle cost model.

The results indicated that eLHDs are not yet a universal solution to all underground mining systems. It was found that while eLHDs can offer lower operating costs and do contribute many qualitative benefits, they also have a range of drawbacks, primarily due to their trailing cables. Nevertheless, with a suitable mine design, electric load haul dump units are a viable option and could pave the way for zero-emission electric machinery in the Australian mining industry.

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1. Introduction

1.1 Background

Concerns with the adverse health effects of operating diesel engines in underground mines have risen since their widespread introduction to the industry in the 1960's. Today, a host of organisations (such as the Diesel Emissions Evaluation Program and Manufacturers of Emission Controls Association) are committed to assessing the risks of diesel exhaust, controlling emissions and exploring alternative fuel sources. This has led to the development of a wide range of new technologies; from catalytic diesel particulate filters to hybrid haul trucks and zero-emission underground vehicles.

Diesel particulate matter (DPM) is emitted by diesel engines due to incomplete combustion and impurities in the fuel (de la Vergne 2003). In the last year, there have been major developments in the health risks associated with DPM. As of June 2012, the World Health Organisation has declared DPM a Group 1 carcinogen. This is based on evidence that exposure is linked to an increased risk of developing lung cancer (IARC 2012). Intuitively, these health issues are more immediate underground, and a report by Bugarski et al. (2004) 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 still remain no statutory limits for DPM exposure. Furthermore, exposure regulations (0.1 mg/m^3 and 0.07 mg/m^3 of elemental carbon over 8 hours and 12 hours respectively) are Total Weight Average (TWA) limits, which do not account for brief periods of intense exposure (Raubenheimer & van den Berg 2013). In light of the proven detrimental health effects, one could anticipate that more stringent DPM legislation is probable in the near future.

While a number of alternative fuel sources have been explored for underground 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 are load haul dump units (LHDs).

These machines have two main functions:

1. To muck and load ore at the draw points or in the stopes of underground hard rock mines and haul it to dumping points (Larsson et al. 2005)
2. To load haul trucks at these stockpile areas (AUSIMM 2012)

These vehicles could theoretically be powered by one of three electric options: batteries, overhead power lines 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 & Knights (2013), LHDs required 1.5-2 tonnes of batteries, and this only allowed 2-2.5 hours of working time. Recharge time was then estimated at 2 hours, resulting in an undesirable vehicle availability of around 50%. A battery swap mechanism has been suggested to account for this. 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 manoeuvrability. An umbilical trailing cable plugged into the electrical infrastructure of the mine is currently the most viable way to power electric load haul dump units (eLHDs), and also drill jumbos, long hole drill rigs and electric shuttle cars.

LHDs are typically diesel, however eLHDs are becoming increasingly common (Paterson & Knights 2012). These zero-emission vehicles produce less noise, vibration and heat (Paraszczak et al. 2013), providing better working conditions for employees. There is also economic incentive to consider eLHDs, with potential savings in ventilation, fuel, consumables, regulation checks and maintenance (Miller 2000, Paterson & Knights 2012). However, the limitations imposed by trailing cables present several drawbacks (Paterson & Knights 2012). These include reduced mobility, versatility, cable faults and relocation issues.

Ultimately, any decision concerning the feasibility of eLHDs must consider a range of decision criteria including economic, environmental, social and logistical considerations.

1.2 Objectives and benefits

The objective of this study is to conduct a cost/benefit analysis of eLHDs via a literature review and a life cycle cost model. This analysis would then serve to either justify or preclude the use of eLHDs as a solution to the issues associated with diesel machinery in underground mining systems.

The key motive behind this study is to potentially improve working conditions in Australian underground mines. Additionally, to the author's knowledge, very few diesel/electric LHD comparative studies have been published, and this paper serves to fill this gap in the current literature.

A cost/benefit analysis of eLHDs is of interest to many different parties, as displayed in Table 1.1. The analysis is significant with respect to underground mining corporations' triple bottom line. It is in their best interests to continue to explore alternatives to diesel, which could be better for their employees, the planet and their profit margin. Equally, the study will outline applications where eLHDs are not suitable, and this knowledge could save companies time and money buy *not* investing in this technology.

The study is also of interest to LHD manufacturers. Those that already make electric models are likely to have completed some form of cost/benefit analysis, so this report could act as an additional source to either bolster or challenge previous findings. The analysis could also serve to help refine the design of the eLHDs, by identifying major shortcomings. On the other hand, those manufacturers that do not yet make eLHDs could use the results to decide whether designing new electric models could be justified.

Mining academics and the wider engineering community would be interested in the findings, since alternative fuels sources are now a major engineering consideration due to climate change, sustainability and public perception. The report could also act as a precursor for similar future projects with respect to electric haul trucks, or other heavy machinery. Ideally, this would result in a catalogue of all diesel machinery on mine sites, describing the circumstances under which these can/should be replaced by electric models. Due to constant advances in technology, and the dynamic nature of the economy and fuel prices, these reports would require regular updates; and so this report would serve as a framework.

Table 1.1: Parties interested in the study

Party	Potential Benefit/Interest
Underground mining companies	– Improve triple bottom line
LHD manufacturers	– Confirm/deny previous studies – Refine design – Contribute to decision of whether to design electric model (if not currently making)
Mining academics, engineering community	– Current focus on climate change and sustainability – Predecessor for future work with other machinery
Mining associations, unions, government departments	– Help develop new legislation/policies

Finally, this analysis is of importance to the many organisations, mining associations, workers unions and government bodies worldwide that are aware of the risks of diesel exhaust, and have the power to push for legislation changes. In Australia, these include the Mine Ventilation Society of Australia (MVSA), State Department of Mines and Petroleum, Safe Work Australia, and the Construction, Forestry, Mining and Energy Union (CMFEU). Other notable organisations in the USA include the Clean Air Task Force (CATF), Diesel Emissions Evaluation Program (DEEP) and the Mine Safety and Health Administration (MSHA).

2. Literature Review

2.1 Overview

The literature review represents a major component of this project, and so is presented as a separate section. The review was broken up into seven subheadings: health, ventilation, comparison, trailing cables, previous studies, other measures, and future diesel prices. While some of the data used for the LCC model has been included here, research regarding costs is predominantly presented in the *Justification of Inputs* (Section 3.4).

2.2 Health

Perhaps the most documented motive to seek alternatives to diesel is health. A report by Schneider & Hill (2005) estimated that DPM shortens the lives of nearly 21,000 people in the U.S. every year. A number of recent epidemiological studies specific to the underground mining industry (Attfield et al. 2011, Silverman et al. 2011) have demonstrated an increased risk of lung cancer due to DPM exposure. As mentioned, these have culminated in the World Health Organisation declaring DPM a Group 1 carcinogen.

In addition, 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 recognised 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 (Correy 2013).

Furthermore, Hedges et al. (2007) state that short-term exposure to DPM can hamper the respiratory and immune systems, particularly for those with asthma or allergies. Hartman et al. (1987) discuss another health issue arising from diesel machinery, which is high noise level. Moore (2010) advises that the average noise level for electric vehicles is 85dB, in comparison to 105dB for diesel vehicles.

2.3 Ventilation

A second driving force for the replacement of diesel machinery in underground mines is ventilation costs. According to Tuck (2011), ventilation in underground mines is required for the following reasons:

- To provide oxygen to personnel
- To provide oxygen for combustion
- To dilute fumes from diesel engines and blasting
- To regulate heat due to machinery and geothermal gradient of strata
- To dilute DPM
- To improve visibility

De la Vergne (2003) states that ventilation typically accounts for over one third of the electrical operating costs of an underground mine, while Paraszczak et al. (2013) suggest this figure is up to 40%. Both Halim & Kerai (2013) and Paraszczak et al. (2013) conclude that use of zero-emission electric vehicles, with approximately one third of the heat emission of their diesel counterparts, *will* reduce ventilation requirements. Furthermore, Paraszczak et al. (2013) 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), stipulate a ventilation requirement of $0.05m^3/s$ per kW of diesel engine power if the maximum exhaust gas emissions of the engine in a diesel unit contain less than 1000ppm of nitrous oxides and less than 1500ppm of carbon monoxide. If emissions are above these thresholds, then the requirement is raised to $0.06m^3/s$ per kW. Table 2.1 shows diesel fume dilution rates around the world. WAMSIR 1995 also specifies a minimum flow rate of $2.5m^3/s$ where diesel machinery is operated. However, the only regulation in place for electric vehicles (EV's) is that a minimum air velocity of 0.25m/s is to be maintained, which is independent of motor size.

Table 2.1: Diesel fume dilution requirements around the world (Source: Tuck 2011)

Location	Diesel Airflow Requirement ($m^3/s/kW$)
Western Australia	0.05
Queensland	None
Ontario, Canada	0.06
Manitoba, Canada	0.92
United Kingdom	None
United States	0.032 - 0.094
Chile	0.063
South Africa	None
Indonesia	0.067

A study by Halim & Kerai (2013) aimed to quantify ventilation standards for EV's. 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 EV's should be $0.04m^3/s$ per kW – a 20% reduction. For shallow mines, the EV requirement was advised to be $0.025\text{-}0.037m^3/s$ per kW, dependent upon thermal conditions.

Interestingly, WAMSIR 1995 regulation 10.52, sub-regulations 8 and 9 state that diesel ventilation requirements can be reduced if the inspector is satisfied that exhaust gases from any engine or engines will be diluted to an acceptable level due to one of the following:

- Special design features on an engine
- Exhaust gas monitoring methods and equipment
- Particular operating and engine maintenance practices
- Use of low emission fuel

However requirements cannot be reduced beyond $0.03m^3/s$ per kW where exhaust gas contains less than 1000ppm of nitrous oxides and less than 1500ppm of carbon monoxide, and not below 0.05 m^3/s per kW otherwise. What is important to note is that

WAMSIR 1995 regulations are based on dilution requirements for nitrous oxides and carbon monoxide. There is no guarantee that these will also satisfy the guidelines of 0.1 mg/m^3 (8hr TWA) and 0.07 mg/m^3 (12hr TWA) of elemental carbon mentioned earlier.

2.4 Diesel/electric comparison

Miller (2000), Hartman et al. (1987), Paterson & Knights (2012), Chadwick (1992, 2010) and Paraszczak et al. (2013) all evaluate the relative technical pros and cons of diesel and electric machinery in mining. The sources tend to concur that while diesel vehicles tend to be more mobile and versatile, they may incur larger operating costs due to fuel, consumables (e.g. filters, lubricants), ventilation and regulation checks. It is also proposed that the reduced noise, vibration, emissions and heat of electric vehicles can result in better working conditions, especially underground.

Bakshi & Bakshi (2009) offer some additional merits of the electric drive system. These are:

- Control characteristics can be adapted to application requirements
- Simple and easy speed control methods
- Electric braking can be applied easily
- Function in a variety of work environments (e.g. explosive, radioactive and submerged)

There is some uncertainty concerning relative productivity rates. While the operational flexibility of diesels generally renders them more productive, Miller (2000) offers that constant regulation checks can hamper productivity. According to Chadwick (1992) and Paraszczak et al. (2013), 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.

Paraszczak et al. (2013) also state that due to the higher efficiency of electric drives, eLHDs can be equipped with less powerful motors, leading to lower comparative energy consumption. Another point raised in this paper 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. These reductions in loading/dumping times can result in shorter cycle times, and therefore increase productivity. A full discussion of productivity is provided in Section 5.3.

2.5 Trailing cables and mine design

The major source of eLHD issues is the umbilical trailing cable, which is plugged into the mine's underground electrical infrastructure. Drawbacks include restricted movement, limited haul range, cable wear and interference with autonomous light barriers (Paterson & Knights 2012). Chadwick (1992) also cites cable reel issues and related expenses as shortcomings of electric equipment, but suggests 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. (2013) suggest electric loaders must tow a portable diesel generator. Eric Williams, Principal Ventilation Engineer with Barrick Gold and member of MVSA, advised the only other option is to tow the eLHD by one of its diesel counterparts. This then affects the utilisation of each machine, which in turn results 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. Paterson & Knights (2012) dictate 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.

Paraszczak et al. (2013) describe another possible drawback, which is the restriction imposed by the maximum length of the cable. Logically, short cables offer low cost, weight and electrical losses, but low range. Cables that are too short may require future replacement (Paterson & Knights 2012). Longer cables add range, but may contribute unnecessary weight and cost, and are ultimately limited by electrical losses. Cable length is dependent upon a wide range of factors, including reel configuration, diameter, voltage and frequency, but in general is between 100-400m (Paraszczak et al. 2013). If the power feed is ideally at the midpoint of the route, the range is in theory twice this distance. Tamrock Corp (1997) states that a typical haulage distance for an LHD is 50-400m, so with suitable cable design, range should not be an issue.

2.6 Previous comparative studies

Previous studies were difficult to obtain, as only a few have been published. Paterson & Knights (2012) reference data sets of 6 eLHDs and 2 diesel LHDs, taken over 414 days at Rio Tinto's Northparkes Mine. Availability, utilisation and maintenance data is shown in Table 2.2. Note that MTBF and MTTR are abbreviations for 'mean time between failure' and 'mean time to repair' respectively. The breakdown of causes of maintenance downtime is shown in Figures 2.1a and 2.1b.

Table 2.2: Availability, utilisation and maintenance comparison (Source: Paterson & Knights 2012)

Drive	Data sets	Mean availability (%)	Mean use of availability (%)	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

Electric loaders demonstrated slightly shorter maintenance times, but also needed maintenance more frequently. Paterson & Knights (2012) concluded that the latter was a significant variation, and was 'indicative of diesel LHDs having a lower failure frequency than eLHDs'. In total, an average of 1660 incidents were recorded per eLHD, and 1415 per diesel. This is reflected in the availabilities, which suggest that for every 100 hours, the diesel LHDs needed around 8 hours of maintenance, while eLHDs required roughly 12hrs – 50% more downtime. This is despite the fact that eLHDs had scheduled maintenance every 500 hours, while the diesels were every 125 hrs. A major factor in this discrepancy is that 15% of eLHD maintenance was due to trailing cable issues and electrical faults, as seen in Figure 2.1a.

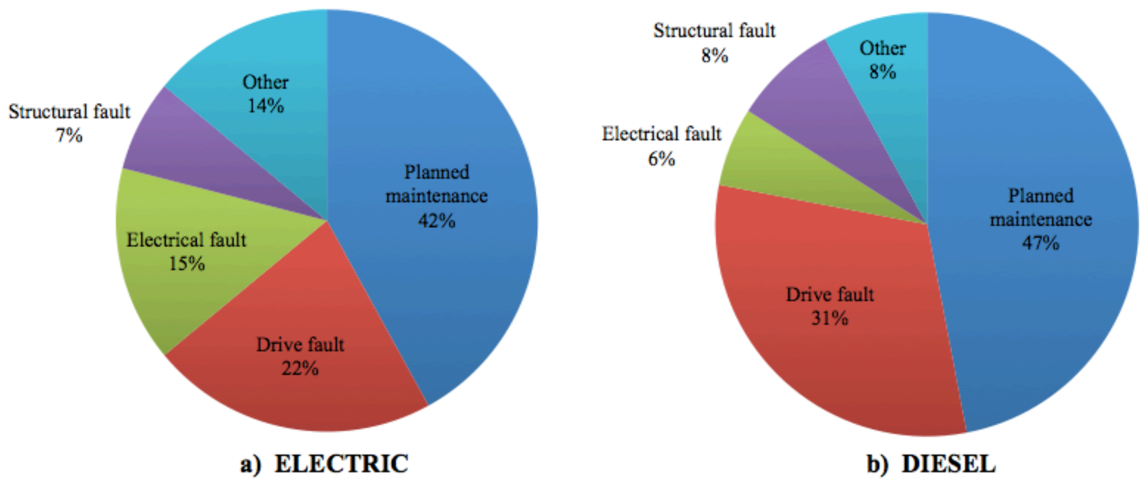

Figure 2.1a and Figure 2.1b: Average maintenance downtime by category for diesel and electric loaders (Source: Paterson & Knights 2012)

Paterson & Knights (2012) propose that the disparity in the 'use of availability' values could be explained by the preference to use eLHDs due to lower operating costs. However, in other applications, diesel machines may exhibit higher use of availability due to their superior operational flexibility.

Data from InfoMine USA (cited in Sayadi et al. 2012 and displayed in Appendix A) compares capital costs, operating costs, capacity, dimensions and power of 11 diesel and 6 electric LHDs. This study will be referenced later in the *Justification of Inputs* section, where it was used to form cost estimates for parametric cost inputs.

The comparative study by Paraszczak et al. (2013) was used extensively, however this study was predominantly a literature review. The main data sources for the Paraszczak et al. (2013) paper were again from InfoMine, as well as Sandvik product specifications retrieved online.

2.7 Other measures for controlling diesel emissions

2.7.1 Overview

There is a long list of other measures that can be employed to minimise diesel emissions underground. These can be categorised into engine controls, exhaust controls, alternative fuels and ventilation considerations. Appendix B displays a list of suggestions, taken from Tomko (2012) for the MSHA, Raubenheimer & van den Berg (2013) for the MVSA and de la Vergne (2003) in *Hard Rock Miner's Handbook.*

Two alternatives were considered in this study and added into the life cycle cost model. These were biodiesel and diesel particulate filters (DPFs). Some background information on each of these alternatives, as well an explanation of engine classification, is included below.

2.7.2 Engine classification

As displayed in Table 2.3, diesel engines are now categorised into stages/tiers based on DPM emissions. Raubenheimer & van den Berg (2013) reveal that currently only Tier 1/Stage I and Tier 2/Stage II type diesel engines are commercially available in underground vehicles, and that some Australian mines still operate with unclassified engines. Tier 3/Stage IIIA vehicles are obtainable, however there are long lead times for delivery, and the introduction of these vehicles saw no change in DPM limit. The paper forecasts that it may be some time before Tier 4/Stage IIIB engines (introduced in 2011) become available to the underground mining industry.

Table 2.3: Diesel engine classification

USA std	Intro year	DPM limit (g/kWh)	Euro std	Intro year	DPM limit (g/kWh)
Tier 1	1996	0.54	Euro Stage I	1999	0.54
Tier 2	2003	0.20	Euro Stage II	2002	0.20
Tier 3	2006	0.20	Euro Stage IIIA	2006	0.20
Tier 4	2011	0.02	Euro Stage IIIB	2011	0.02
			Euro Stage IV	2011	0.01

2.7.3 Diesel particulate filters

Hedges et al. (2007), de la Vergne (2003), Bugarski et al. (2004), MECA (2007), McGinn (2004), and Raubenheimer & van den Berg (2013) all discuss the use of DPFs as a method for reducing the impact of diesel exhaust underground. DPFs are custom exhaust after-treatment devices, which are specifically designed to filter DPM. A range of filtration technologies exists including cordierite, silicon carbide, ceramic, metallic and paper, with varying costs and efficiencies. A schematic diagram illustrating the

DPF filtration mechanism is shown in Figure 2.2.

Bugarski et al. (2004) insist that DPF systems have been shown to effectively reduce DPM emissions in both the laboratory and in underground mine tests. Their results showed 88% to 99% reductions in elemental carbon concentrations. McGinn (2004) agrees, and evaluates that twin ceramic monolith filters with base metal catalyst DPF varieties can exhibit consistent DPM filtration efficiencies of 99%.

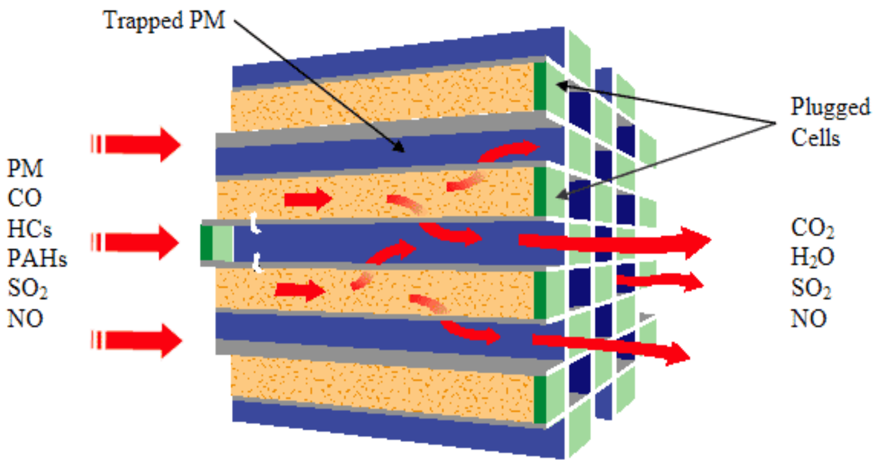

Figure 2.2: Schematic diagram of DPF filtration mechanism (Source: MECA 2007)

In spite of this, Hedges et al. (2007) and McGinn (2004) describe several drawbacks of DPFs. They are not an 'off-the-shelf' technology. Duty cycles and exhaust temperatures must be analysed prior to outfitting vehicles with DPFs since they are designed to operate at a given soot-loading factor, corresponding to an optimum air-fuel ratio. For this reason they require regular inspection and maintenance of the engine. This also entails constant monitoring of exhaust backpressure and temperature, requiring either auxiliary systems or interfacing these parameters with existing electronic engine controls. Neglecting maintenance can completely ruin filters, which are expensive to replace.

2.7.4 Biodiesel and ULSD

The second alternative that was researched was the use of biodiesel fuel, manufactured from vegetable oil and animal fats. Biodiesel can be used in its pure form (B100) or blended with diesel, e.g. B5 (5% biodiesel) and B20 (20% biodiesel) (EERE 2013).

Testing by Bugarski et al. (2004) demonstrated that biodiesel blends B20 and B50 reduced the elemental carbon concentrations in underground mine air by 26 and 48% respectively. However, due to possible impact on engine durability, vehicle manufacturers may only approve blends up to B5, and some to B20 (EERE 2013).

Biodiesel fuel prices, rebates and consumption are discussed later in Section 4.5.2.

Ultra low sulphur diesel is another fuel option for minimising DPM emissions. Hedges et al. (2007) and de la Vergne (2003) describe how ULSD reduces the sulphate particulates in DPM emissions and allows the oxidation catalysts to function properly. ULSD will not be discussed further though, due to the fact that it is already widespread, and most diesels sold today already have low sulphur content.

2.8 Future diesel prices

The current and future price of diesel fuel plays a substantial role in the economic feasibility of electric machinery. In Australia, the regional market for petroleum products is the Asia-Pacific market. As a result of economic growth in China and India, as well as the mining and commodity boom in Australia, there has been a significant increase in demand for diesel in recent years (AIP 2013). Regional supply has not kept up with this growing demand, and this has caused the recent rise in diesel prices (AIP 2013).

A 2011 report by Syed and Penney for the Bureau of Resources and Energy Economics (BREE) modeled world energy costs until 2035. The report forecasted that as oil demand continued to increase with stronger economic growth, and with the availability of spare production capacity and stocks in OPEC, world oil prices would remain relatively constant over the medium term.

Syed and Penney (2011) were much less certain of long-term oil prices. They identified the cost of developing remaining oil reserves, the volume and timing of investment in production and refining capacity, and technological development in relation to alternative liquid fuels as factors expected to drive long-term oil prices. Alternative liquid fuels (such as gas-to-liquids and second generation biofuels) could potentially keep oil prices down, despite a projected rise in the marginal cost of oil production. The results of the model are depicted in Figure 2.3, where energy prices at the end of the 2008-2009 financial year are taken as 100. The figure depicts a gradual 50% increase in real world oil prices over the next 20 years.

While crude oil and diesel are different products traded on separate markets, diesel is a refined product of crude oil, and hence is (to a degree) dependent on crude oil prices. The parallel nature of the plots in Figure 2.4 (across page) illustrates this relationship.

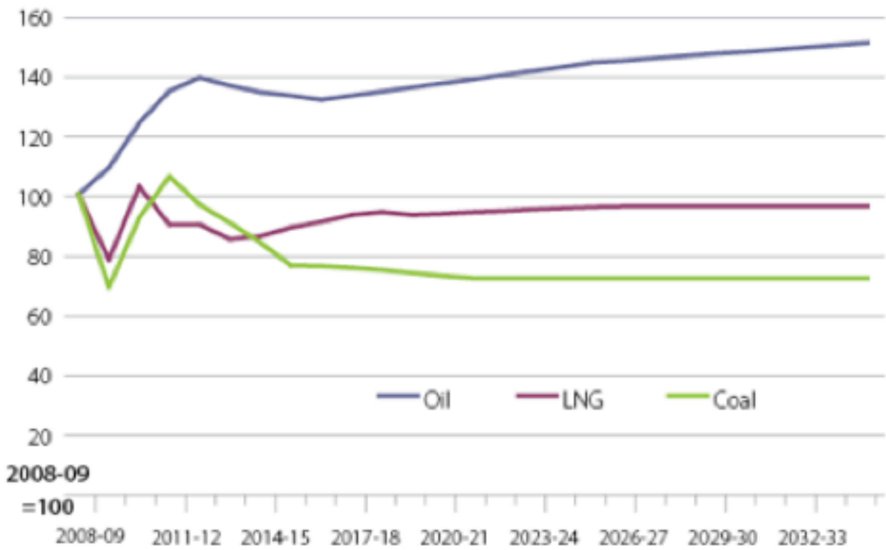

Figure 2.3: Real projected world energy prices (Source: Syed & Penney 2011)

US diesel fuel and crude oil price projections by the US Energy Information Administration (EIA 2013) are shown in Figure 2.4. EIA forecasts a gradual decline in US crude oil and diesel prices over the next year, which is actually consistent with the negative gradient of Figure 2.3 over the same time period.

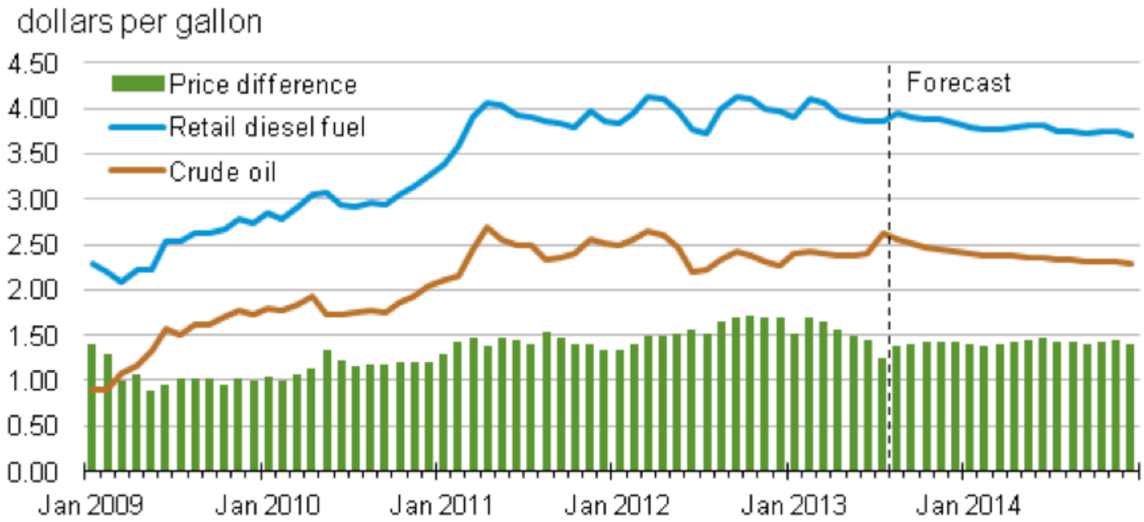

Figure 2.4: US diesel fuel and crude oil prices (Source: EIA 2013)

Note: At the time of writing, diesel costs have spiked, largely related to the crisis in Syria. West Texas Intermediate (WTI) oil prices peaked at a two year high of US$110 per barrel in late August 2013, and are currently (October 2013) at around US$104 per barrel (Oil-price.net 2013). Again, current diesel fuel prices and rebates are all discussed in Section 3.4.5.

2.9 Summary

In summary the key outcomes of the literature review are:

- DPM has been declared a carcinogen, and tougher exposure and ventilation regulations are likely to follow.
- Ventilation accounts for around 40% of an underground mine's electrical costs, and electric vehicles can bring significant savings.
- Diesel vehicles have more operational flexibility, however may incur larger operating costs.
- The major drawback for electric vehicles is their trailing cable.
- There are a number of other measures to control DPM emissions.
- Diesel fuel prices are forecast to remain relatively stable in the short term.

3. Model Formulation

3.1 Life cycle cost model development

Standards Australia's *Life cycle costing – An application guide* (1999) was used to help develop the life cycle cost (LCC) model. This document states that an LCC model 'abstracts the salient features and aspects of the product and translates them into cost figures'. A representation of the function of an LCC model is displayed in Figure 3.1. It should be noted that, strictly speaking, an LCC model entails product disposal at the end of its life cycle. The model used only includes the acquisition and operation phases of the product life cycle, and assumes there will be no disposal within the 10-year period considered.

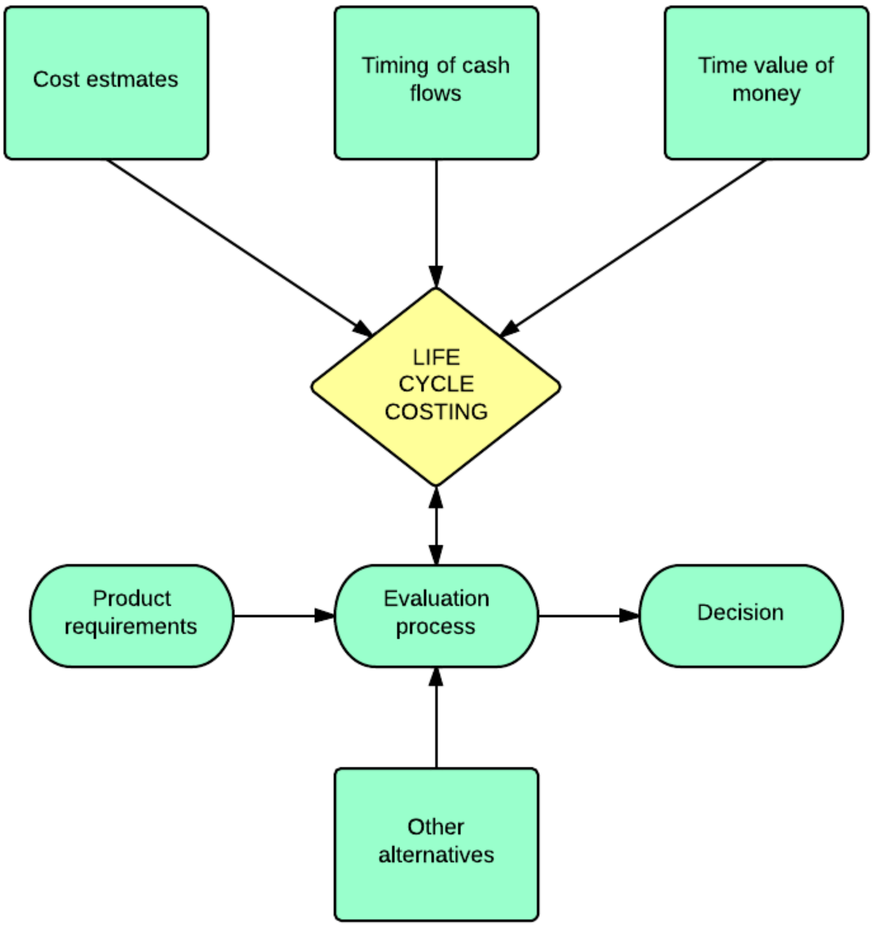

Figure 3.1: Life cycle costing (adapted from Standards Australia 1999)

The two main purposes for life cycle costing are specified as the evaluation of alternatives and financial planning (Standards Australia 1999). The former is particularly relevant to this study. The standard describes the main steps in LCC modelling as:

1. Adoption of cost breakdown structure (CBS)
2. Identification of insignificant cost elements
3. Choice of cost estimation methods
4. Data acquisition
5. Integration of individual cost elements
6. Identification of uncertainties
7. Review

Throughout the literature review, the CBS was developed and costs were broken down into individual elements. These were categorised into headings named fleet, fuel, usage, consumables, maintenance and ventilation. Since this is a comparative study, elements that were considered constant for both diesel and electric loaders, for example operating labour, were dismissed. It was decided that a parametric costing method would be employed, which uses significant parameters and variables to develop cost element relationships in the form of equations (Standards Australia 1999). This way, dimensional reasoning could be used to convert between units and link cost elements.

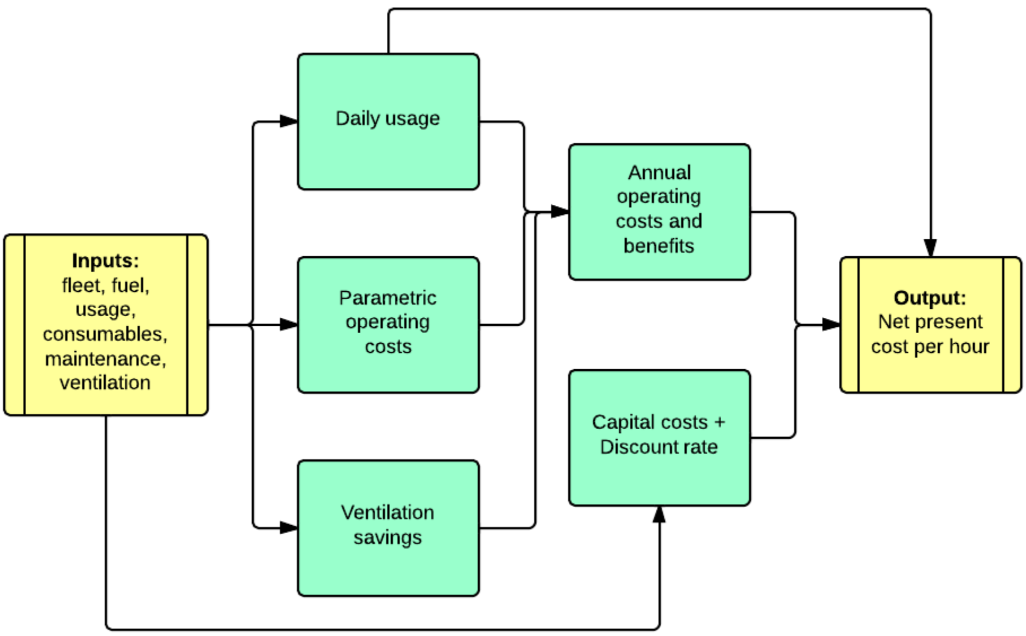

Figure 3.2: Basic cost model configuration

Data acquisition was performed throughout the literature review, and is summarised in Section 3.4. Parametric cost elements were linked using Microsoft Excel. A simplified LCC model configuration can be seen in Figure 3.2, while spreadsheet screenshots are attached in Appendix C. This shows how cost elements (inputs) were used to calculate daily operating costs, usage hours and ventilation savings, which were in turn extrapolated to annual costs. The input cost elements are specified in real costs (2013 Australian dollars), however it was deemed that discounting using net profit cost (NPC) metrics was also necessary. Operating costs were then combined with capital costs and discount rates to obtain net present costs, and divided by operating hours to give an output that represented a discounted hourly cost.

A full description of the NPC model is included in Section 3.3. This decision to include discounting was made based on the list of discounted costs uses defined in *Life cycle costing – An application guide*. These include:

- Products with long lives
- Assessing the impact of new technology
- Cost/benefit analysis
- Determining the economic viability of products
- Evaluation and comparison of alternatives

3.2 Ventilation cost modelling

The parametric cost modelling technique used was straightforward, with the exception of the ventilation section. To understand the way in which this was modelled, some mine ventilation theory is needed first. This is given by Tuck (2011).

The square law of mine ventilation is:

$$p = RQ^2 \tag{3.1}$$

where

$p =$ pressure across airway (Pa)

$Q =$ air flow rate (m^3/s)

$R =$ mine (or Atkinson) resistance (Ns^2/m^2) – a measure of the resistance to airflow of duct, dependent upon many factors, including duct length, duct cross sectional area, friction and air density.

Air power P (W) is then defined as:

$$P = pQ \tag{3.2}$$

Substituting Equation 3.1 gives:

$$P = RQ^3 \tag{3.3}$$

This demonstrates a cubic relationship between air power and flow rate. For example, if the air flow rate in the mine were to be doubled, this would require an eight-fold increase in air power provided by the fans. Since air power is directly proportional to cost (prices given as \$/kWh), this would also require eight times the initial ventilation cost.

With this relationship in mind, it was difficult to break down ventilation costs into components, as had been done with other input parameters such as consumables and maintenance. This was due to the fact that the relationship was non-linear, and a small change in required volume flow resulted in a large change in air power and hence cost.

If ventilation due to loaders were calculated in isolation, the procedure would be to multiply ventilation requirement by motor power, to then convert this flow rate into an air power using Equation 3.3 and to finally multiply by operating hours and cost per kWh. For example, consider a Western Australian underground mine with 4 diesel LHDs rated at 250kW each. The mine has a 2000kW ventilation system and a volume flow rate of around $215\text{m}^3/\text{s}$, giving a fairly typical resistance of roughly $0.2\ \text{Ns}^2/\text{m}^2$.

The loader component of ventilation required could be calculated as:

$$Q = 0.05 m^3 s^{-1} kW^{-1} \times 4(250) kW = 50 m^3 s^{-1}$$

Using Equation 3.3, the air power is then:

$$P = RQ^3 = 0.2 Ns^2 m^{-2} \times (50 m^3 s^{-1})^3 = 25 kW$$

Assuming the LHDs are operating for 15hrs per day, and that electricity costs \$0.2/kWh this gives a daily ventilation cost per vehicle of:

$$C = \frac{25kW \times 15hr \times \$0.2 / kWh}{4} \approx \$20 / day / unit$$

This is a misleadingly low ventilation cost, due to the cubic relationship between air power and flow rate.

When interviewed on 20 September 2013, Eric Williams suggested a different approach. Rather than considering the cost of ventilation per unit, a more practical method would be to quantify ventilation *savings* due to electric vehicles. Consider the same example described above. With no eLHDs present, no possible savings are available. Now consider if two of these vehicles were substituted for 150kW electric models.

The new ventilation volume requirement (assuming an EV regulation of $0.03m^3/s/kW$) would be:

$$Q = 0.05m^3s^{-1}kW^{-1} \times 2(250)kW + 0.03m^3s^{-1}kW^{-1} \times 2(150)kW = 34m^3s^{-1}$$

This represents a potential mine flow rate saving of:

$$\frac{50m^3s^{-1} - 34m^3s^{-1}}{215m^3s^{-1}} \times 100\% \approx 7\%$$

Now using Equation 3.3, a 7% saving in volume equates to a power saving of around 20% since:

$$P = R(0.93V)^3 = 0.8RV^3$$

Assuming 24 hour operating time of the ventilation system, and that the fans are running at 100% capacity, the daily electricity cost due to ventilation for this mine is:

$$2000kW \times 24hr \times \$0.2 / kWh = \$9600 / day$$

Finally, if a 20% saving in ventilation costs were possible, this would correspond to daily savings of:

$$\$9600 / day \times 20\% \approx \$1900 / day$$

This reveals daily savings per eLHD of almost $1000/day.

In summary, the ventilation constituent of the cost model was configured around a ventilation savings approach. Ventilation costs are taken as zero for diesel machines, and then the potential savings are calculated for electric loaders. 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. Appropriate values (see Section 3.4.12) were suggested by Williams, however the model was designed with the intention that individual mines could enter their own ventilation specifications and calculate costs accordingly.

3.3 NPC metrics

The final sheet of the model (see Appendix C) features a net present costs (NPC) calculation over a ten-year period. This takes the capital cost of acquiring an LHD, and adds annual operating costs, which are discounted to present day costs in Australian dollars. In the case of eLHDs, this also includes negative costs (benefits), due to the ventilation cost savings described above.

This governing formula is:

$$PV = \frac{FV}{(1+r)^n} \tag{3.4}$$

where:
PV is the present value
FV is the future value
n is the number of years
r is the discount rate (dependent on interest rate and risk – chosen as 9%)

NPC calculations are important when considering costs over a period of time, in that they account for the time value of money with respect to both timing and risk aspects of future cash flows (Hodkiewicz 2013). In this sense, NPC modelling penalises uncertainty around if/when cash flows will occur, as well as uncertainty around the magnitude of these cash flows.

Since this cost model compares electric/diesel NPC per unit after 10 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 penalise a machine with a higher utilisation. Consequently, the output of the cost model was decided to be a net present cost calculated over 10 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 above.*

3.4 Justification of inputs

3.4.1 Estimation techniques

Two editions of AUSIMM's *Cost Estimation Handbook for the Australian Mining Industry* (1993, 2012) have been used to make estimates. The older edition of the Cost Estimation Handbook had more content with regard to LHD units, and so has been used more prominently. Data from InfoMine USA, referenced in Sayadi et al. (2012), was also used and is attached in Appendix A.

Values used from the 1993 edition of the *Cost Estimation Handbook* have been adjusted to account for the large cost escalation in the Australian mining industry, due to the following factors (as prescribed in the 2012 edition):

- Massive growth in the industry
- Inflation
- Increased risk management, especially with respect to safety, environmental impact and social issues
- Tighter legislation
- Higher quality standards
- Developments in technology
- Increased complexity of mining scenarios

Lin et al. (2006) dictate that the core components contributing to quality data are accuracy, relevance, fineness, and timeliness. It is acknowledged that a lot of the data used to make estimates, while relevant, lacks timeliness or accuracy or both. For this reason, sensitivity analysis was carried out in the *Results* section, along with considerations relating to unstable variables such as fuel and electricity costs. The relatively poor data quality can be attributed to a lack of previous studies in this area. Base input values are displayed across the page in Table 3.1.

Table 3.1: List of base cost model inputs

Input	Units	Value Range		
		Diesel: Sandvik LH514	**Electric: Sandvik LH514E**	**General: Both Models**
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

3.4.2 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, Mount Isa Copper Mine has 25). The default fleet number was selected as eight loaders. The fleet combination was chosen as 4 diesels and 4 electrics, so that total hourly costs could be compared without adjusting for fleet size.

For this study, only one size of LHD was considered. This was the large capacity LHD (~15 tonne payload), which is the most common size of LHD in Australian hard rock mining, again according to the Australia's Mining Monthly (2011). The Sandvik LH514 and LH514E models were chosen as a suitable pair of similar diesel and electric machines. The specifications of these machines are displayed in Table 3.2.

Table 3.2: Selected Sandvik LHD specs

Drive	Sandvik Model	Bucket Capacity (m^3)	Tramming Capacity (tonnes)	Unloaded Weight (tonnes)	Power (kW)
Diesel	LH514	5.4	14.0	38.1	256
Electric	LH514E	5.4	14.0	38.5	180*

* This value is inclusive of auxiliary motors for hydraulics and fans, and so represents the total installed power of the machine.

3.4.3 Unit capital cost

According to Moore (2010), eLHDs have a capital cost approximately 20% higher than a similar diesel unit. Paraszczak et al. indicate that an electric loader with a bucket capacity of $1.5m^3$ costs approximately 30% more than an identical diesel machine. However, for bigger loaders, this difference is between 20 and 25%. AUSIMM (2012) suggests that a 13-15 tonne capacity diesel LHD will cost around AUS$1 million in real 2010 prices. This is supported by the data from InfoMine USA (cited in Sayadi et al. 2012), which indicates a reasonable price for a large diesel loader is around $AUS1-1.1 million, and $AUS1.2-1.3 million for an electric model. The default values were selected as $AUS1 million and $AUS1.2 million respectively.

3.4.4 Discount rate

A common discount rate is somewhere in the range 6-10%. The chosen default value was 9%.

3.4.5 Fuel price

Based on the Australian Institute of Petroleum's weekly diesel report (week ending 6 October 2013), the terminal gate price (TGP) or wholesale price for diesel is currently around AUD$1.45/L. This is prior to diesel fuel rebates offered by the Australian government. As of July 1 2013, these rebates were cut by 6c/L in the mining industry to around 32c/L (ATO 2013). This gives a revised fuel price of AUD$1.13/L.

3.4.6 Fuel consumption

Based on AUSIMM's Cost Estimation Handbook for the Australian Mining Industry (1993), a realistic diesel consumption rate for a large LHD is 40L/hr.

3.4.7 Engine/motor power

Diesel engine and electric motor power ratings were sourced from Sandvik product specifications available online. These were 256kW for LH514 and 180kW (total installed power) for LH514E.

3.4.8 Electricity price

Electricity price is a highly 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 Section 4.4.2.

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.

3.4.9 Availability and utilisation

The term 'availability' refers to the percentage of calendar time that a unit is available. The complement of availability is downtime, which is a sum of both scheduled and unscheduled maintenance. As such, availability is purely dependent on maintenance. The ‘use of availability’ is the portion of available time that a machine is actually used. This is dependent upon operational and logistical considerations, as discussed below. The product of the availability and the use of availability is the utilisation of the unit.

The main source used to make estimations with regard to usage was the Northparkes Mines data cited by Paterson & Knights (2012) and presented earlier in Table 2.2. Again, the values for availability and use of availability were 92% and 67% respectively for diesel LHDs, and 88% and 67% for eLHDs.

AUSIMM (2012) notes that availability is also dependent upon the condition and age of the machine, and offers some typical rates with respect to condition. Despite this data only specifying open cut machinery; one could assume that the availability of an LHD would be similar to a front-end loader. Also assuming 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 electric vehicles.

Table 3.3: Typical availabilities for open pit machines (Source: AUSIMM 2012)

Condition	New	New	Old	Old
Availability	**Good**	**Poor**	**Good**	**Poor**
Electric shovel	0.92	0.88	0.82	0.75
Hydraulic excavator	0.90	0.86	0.77	0.70
Front-end loader	0.88	0.84	0.75	0.65
Truck	0.90	0.85	0.75	0.65

Use of availability is very site-specific and depends on operating philosophy, roster, management efficiency, shift changeover and fleet size, among other things (AUSIMM 2012). 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 favourable due to their potential lower operating costs.

3.4.10 Consumable cost

AUSIMM (2012) notes that consumable costs are highly dependent on LHD size and working conditions. Reasonable hourly costs per unit (derived from AUSIMM 1993) for lubricants were deemed to be $8/hr for diesel and $5/hr 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/hr/unit was decided upon for basic engine filters. Installation of DPFs is another option, discussed later in Section 4.5.3.

LHD tyre life is heavily dependent upon work conditions and road surface, and typically lies in the range 400-1400 hours, with an average of 800hrs (AUSIMM 1993). Tyres were estimated at $15/hr/unit in each case.

It must be noted that consumable and maintenance costs are specified in usage hours (obtained from utilisation rates and typically around 14 hours per day), rather than 24 hours per day. This is since costs have been derived from the number of engine hours before maintenance or replacement is required, as shown in Table 3.4.

Table 3.4: Required loader maintenance (Source: AUSIMM 2012)

Item	Life (engine hours)
Major overhaul	10000
Transmission	8000
Final drives and brakes	8000
Articulation joint	8000
Loader linkage	8000
Radiator group	8000
Torque converter	6000
Differential	6000
Transfer box	4000
Cockpit	4000
Bucket repair	1000
Minors	250
Unscheduled	250

3.4.11 Maintenance cost

Moore (2010) notes that electric loaders are generally considered cheaper to maintain. Paraszczak et al. (2013) propose that electric motors are easier to maintain, require less qualified personnel and less sophisticated tooling. However, Paraszczak et al. (2013) 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* (1993), it is estimated that diesel machines incur a maintenance cost of around \$70/hr. 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/hr. This is due to savings in engine and transmission maintenance.

It must be noted that these values are purely for materials, so the labour costs of fitters, mechanics or automotive electricians performing the maintenance must also be accounted for. AUSIMM 1993 estimates this is around 40-50% of operating labour. Operating labour has not been included in this model since it is assumed there will be no difference between drive systems. For the purpose of estimating maintenance labour, AUSIMM 2013 quotes the average drill jumbo operator base salary in 2009 Australian dollars as \$160,000. Assuming 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 labour costs at around \$20 per operating hour per unit.

The Northparkes Mines case study presented in Section 2.6 (Paterson & Knights 2012) 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. (2013) estimates maintenance costs of electric LHDs as being approximately 20% higher than for diesel machines. In order to reflect this, maintenance labour 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/hr 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 minimise this cost. In total, the default values summed to $90/hr for diesels and $105/hr (around 17% higher) for eLHDs.

3.4.12 Ventilation specifications

The ventilation requirement for diesel machines was taken from WAMSIR 1995 as 0.05m^3/s/kW. The study from Halim & Kerai (2013) proposed EV ventilation requirements of 0.04 m^3/s/kW for deep mines and 0.025-0.037m^3/s/kW for shallow mines, depending on thermal conditions. The default value was chosen to be 0.03 m^3/s/kW.

Typical ventilation system specifications were provided by Eric Williams when interviewed. These were two primary fans rated at 500kW, doubled to account for booster/secondary fans, and a mine flow rate of 200m^3/s. A ventilation system operating time of 23.5 hours was considered. Ventilation systems are generally run close to 24 hours per day, and the small discrepancy was to account for downtime due to closures or fan maintenance.

4. Results

4.1 Base case results

For the default inputs shown in Table 3.1, the model yielded outputs displayed below in Table 4.1. Again, it is reiterated that the output is a net present cost, calculated over 10 years at a discount rate of 9%, divided by the total operating hours over this period. To reiterate, the model captures the relative savings in eLHDs associated with reduced ventilation and does not include operating labour costs for either unit.

Table 4.1: Base case results

Base Case	Diesel	Electric	Sum
Hourly cost per unit ($/hr)	125.8	85.0	210.8
Total hourly cost ($/hr)	503.3	339.9	843.3

It can be seen that for the base case, the hourly cost per electric loader is around 30% less than that per diesel loader. This confirms the initial expectation that eLHDs can offer reduced operating costs. However, due to the high degree of variability in possible input values, further testing was necessary. First, the effect of fleet number and fleet combination were investigated. This was followed by a sensitivity analysis, and finally an attempt was made at modelling some other DPM mitigation alternatives.

4.2 Effect of fleet number

When analysing combinations of fleet numbers, it became apparent that, for any given set of inputs, the hourly cost per unit for diesel machines did not change. This is a logical outcome, given that operating and capital costs are directly proportional to the fleet number and operation hours. So, the fact that these two variables are accounted for in the output (expressed as cost per unit per hour), means that for a given set of inputs, the diesel cost per unit is independent of fleet number.

This can be seen in Figures 4.1 and 4.2 for total fleet numbers of 6 and 10 respectively. In these figures, the diesel and electric hourly costs per unit are plotted on the left vertical axis, and total hourly costs on the right. 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.

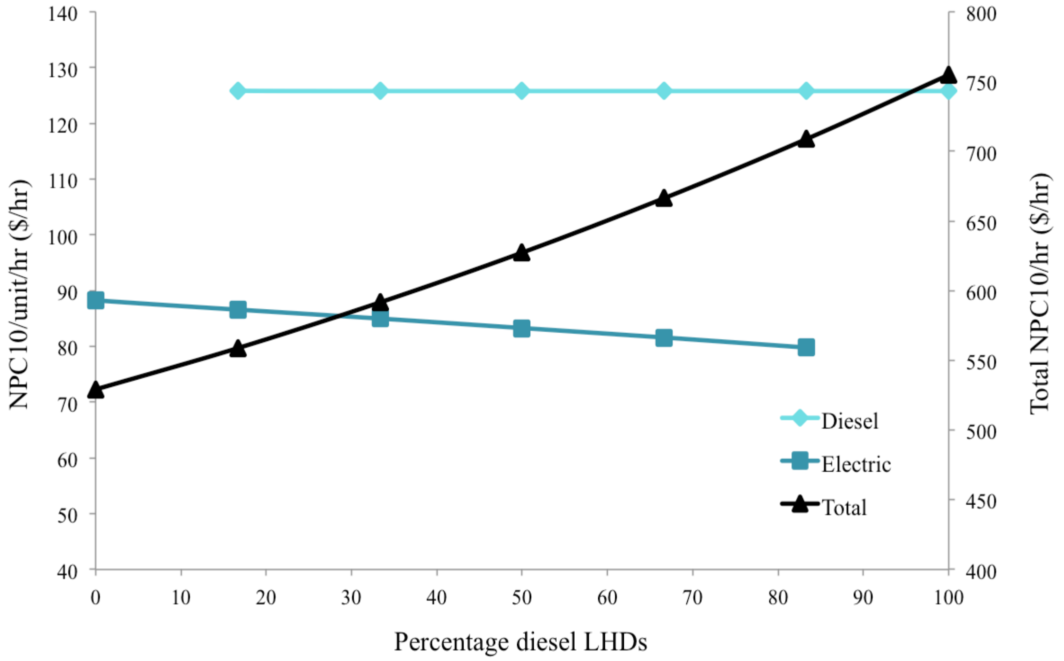

Figure 4.1: Hourly cost for combinations of 6 LHDs (total cost uses right axis)

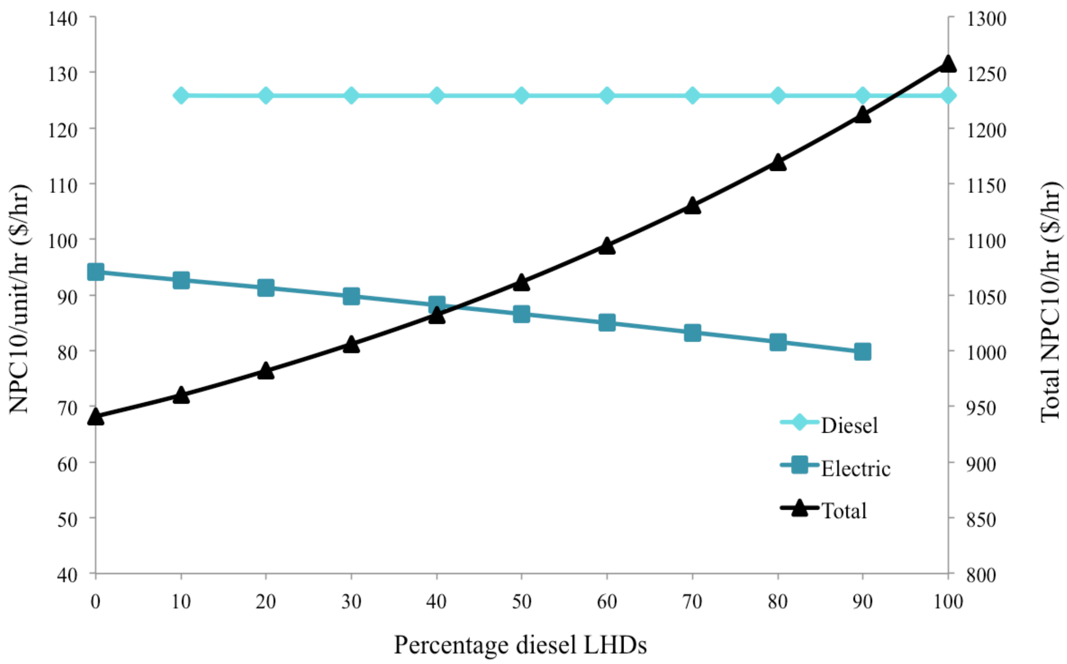

Figure 4.2: Hourly cost for combinations of 10 LHDs (total cost uses right axis)

The reason for this decrease is due to the ventilation savings aspect. The eLHD hourly cost was found to be independent of diesel fleet number, but dependent upon electric fleet number. Figure 4.3 shows that as the number of eLHDs increases, so too does the hourly cost per unit. This can be interpreted as more units having to 'share' ventilation savings. It is a non-linear relationship, and as the number of eLHDs increases, the change in hourly cost decreases.

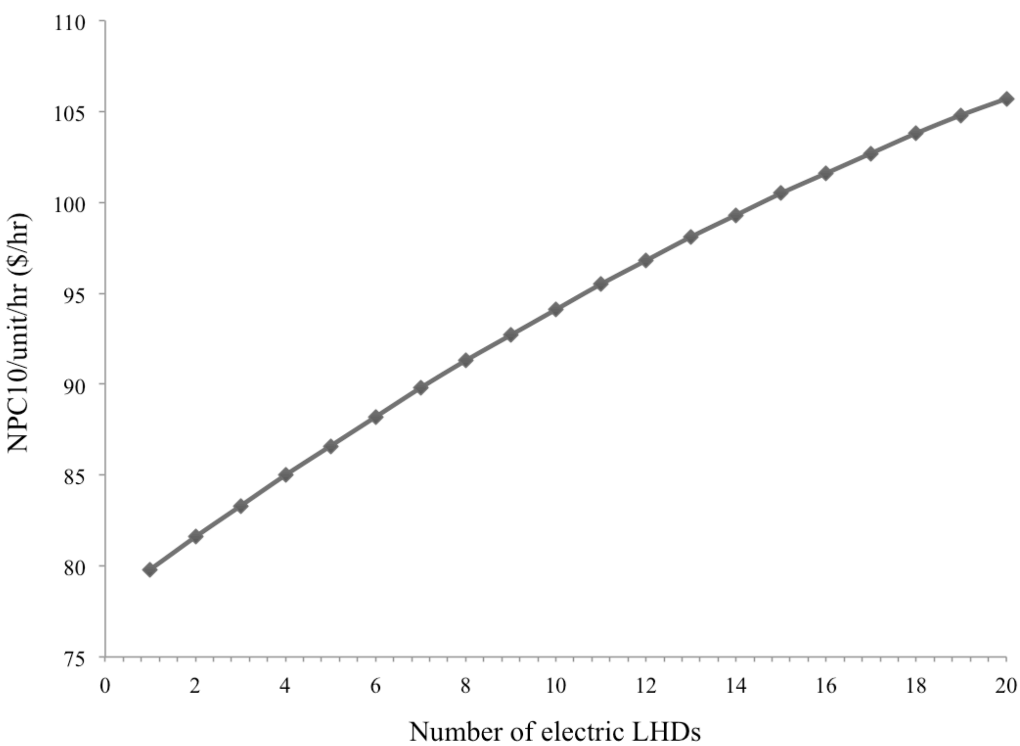

Figure 4.3: Effect of eLHD fleet number on eLHD hourly cost

While this may seem counterintuitive, it is more important to consider total hourly costs, also displayed in Figures 4.1 and 4.2. These plots were obtained by multiplying diesel and electric costs per unit by their respective number of vehicles, and then summing the two. 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 umber of electric units, for realistic fleet numbers (less than 30), this never exceeds the hourly cost per diesel, and so total costs will always rise with a higher percentage of diesel loaders.

4.3 Sensitivity analysis

4.3.1 Method

Using default inputs, a sensitivity analysis was performed on the model. To do this, inputs were varied by 10%, and the change in hourly cost per unit with respect to the base case was noted. Results are displayed in Table 4.2.

Table 4.2: Sensitivity analysis

Alteration	Hourly cost per unit ($/hr)			% Change in Sum
	Diesel	Electric	Sum	
Base	**125.8**	**85.0**	**210.8**	**-**
10% rise in diesel capital	127.8	85.0	212.8	0.9
10% rise in diesel fuel price or consumption	128.7	85.0	213.7	1.4
10% rise in engine/motor power	125.8	83.6	209.4	0.7
10% rise in electricity cost	125.8	83.0	208.8	0.9
10% rise in diesel availability	124.1	85.0	209.1	0.8
10% rise in diesel consumables	127.8	85.0	212.8	0.9
10% rise in diesel maintenance	131.6	85.0	216.6	2.8
10% drop in electric ventilation requirement	125.8	82.4	208.2	1.2
10% rise in total vent power	125.8	80.7	206.5	2.0
10% rise in initial air flow rate	125.8	88.3	214.1	1.6
10% drop in daily ventilation operation	125.8	89.3	215.1	2.0

Three important outcomes resulted from the sensitivity analysis, which were then investigated in the following sections.

- The most significant sensitivities are maintenance and ventilation.
- Increasing electricity costs actually decreases eLHD operating costs.
- Similarly, raising the total power of the ventilation system (dependent upon the primary fan power, number of primary fans and auxiliary adjustment factor), decreases eLHD hourly costs.

4.3.2 Maintenance

Parts and labour costs were subject to increases of 10-100% and decreases of 10-50%. The discrepancy in margins here is since zero maintenance costs are not feasible, while blowouts in maintenance costs may be applicable to scenarios where conditions are severe or vehicle management is poor.

The results demonstrated a linear relationship, whereby 10% increases in maintenance costs caused total hourly costs to rise by around $50. The implications of this finding are detailed in the *Discussion* section.

4.3.3 Ventilation

The same procedure was carried out for total ventilation power as was performed for maintenance. It was found that for every 10% that the ventilation power varied, total hourly LHD costs changed by around $17. However, this was a negative linear relationship, whereby raising ventilation power actually decreased hourly costs. A larger ventilation system results in higher ventilation costs, which in turn means greater ventilation savings are possible. It should be noted that increasing the rating of the ventilation system 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.

It is plausible that the ventilation requirements for electric vehicles may be significantly lower than the default value of $0.03m^3/s/kW$. This is due to EV's 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 & Kerai (2013), however no other studies were found that have attempted to quantify electric vehicle ventilation requirements.

This was investigated by plotting hourly cost of eLHDs against EV requirements of 0-$0.05m^3/s/kW$, shown in Figure 4.4. A ventilation requirement of zero is not actually feasible, since employees require oxygen, and electric machine do still emit some heat.

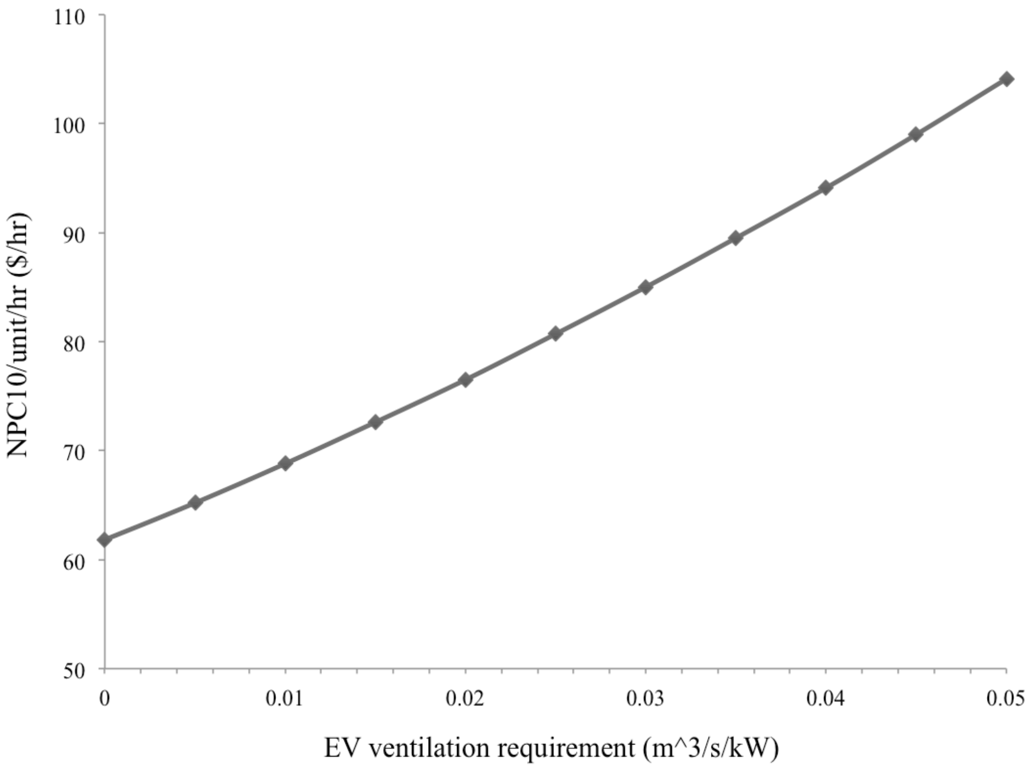

Figure 4.4: Effect of EV ventilation requirement on eLHD hourly cost per unit

Referring to Figure 4.4, a non-linear relationship is evident, with changes in hourly cost per unit becoming slightly larger with higher ventilation requirements. Logically, this is a positive relationship, where higher ventilation requirements result in higher costs. If we multiply costs by four to obtain total hourly costs, it can be seen that if the EV ventilation requirement can be lowered down to, for example, $0.01m^3/s/kW$, this would bring significant hourly savings of approximately $65.

4.4 Energy prices

4.4.1 Diesel fuel price

Despite Syed & Penney (2011) and EIA (2013) predicting relatively stable oil and diesel prices in the short-term, analysing the effect of diesel fuel price was deemed necessary due to the uncertain future of world politics, diesel rebates and carbon taxing schemes.

Without discounting, the diesel hourly cost per unit would be directly proportional to the diesel fuel price, and would rise with a gradient equal to the consumption of the unit (40L/hr). This is confirmed when a discount rate of 0% is entered. However, due to the

NPC discounting used in the model, this gradient becomes 25.7 L/hr. This means that for every \$0.1/L that the diesel price rises (or drops), the output will rise (or drop) by \$2.6/hr per diesel unit.

4.4.2 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 (like diesel prices) are relatively unstable. Furthermore, the default case only considered grid electricity. Many Australian mines are off the grid, so price of electricity generation should also be taken into account.

A number of options are available for electricity generation. Eric Williams suggested that 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 (2013) and Parkinson (2013) 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 (Lazenby 2013).

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 kW) being much larger than the power of the loaders (each around 180kW). Therefore as electricity prices increase, the effective hourly cost to operate an eLHD actually drops. For the default settings, every \$0.01 that the electricity price increased was found to decrease total hourly costs by around \$4.

4.5 Other alternatives

4.5.1 Ventilation requirements

Studies have demonstrated significant reductions in DPM when either biodiesel was used in place of standard petroleum diesel (Bugarski et. al 2004), or if diesel particulate filters were installed (Bugarski et. al 2004, McGinn 2004). Under regulation 10.52, sub-regulations 8 and 9 of WAMSIR 1995, it is possible that if a substantial reduction in emissions is proven, ventilation requirements can be dropped down to as low as $0.03m^3/s/kW$ for diesel engines.

Although it is not certain that the use of either of these alternatives would warrant the reduction of ventilation requirements, this was investigated nevertheless in order to provide a 'best case' scenario for diesel loaders.

Since the model was not designed to accommodate for ventilation savings by diesel loaders, a different approach was used. The volume saving due to diesel loaders was obtained by subtracting the flow rate calculated with the $0.03m^3/s/kW$ requirement from that of the $0.05m^3/s/kW$ requirement. This, as a percentage of the default total mine flow of $200m^3/s$, gave the percentage volume flow. This value could then be temporarily inputted into the model to compute the ventilation savings per vehicle, which was finally manually added to the diesel NPC model as a benefit.

A number of other considerations should be made when assessing the merits of biodiesel and diesel particulate filters (DPFs), and these are included in the *Discussion*.

4.5.2 Biodiesel

To model the use of biodiesel, fuel cost was unchanged. In Australia, TGP biodiesel prices are currently a few cents per litre more expensive (National Biodiesel Limited 2013), but it also receives slightly larger rebates (ATO 2013). Biodiesel was modeled with 5% higher fuel consumption, due to its slightly lower energy content (EERE 2013). These factors depend on the blend of the biodiesel, however for the purposes of this study, an average was taken.

With these alterations, the model outputted a diesel hourly cost per unit of \$98.1, in comparison to the base value of \$125.8, representing an hourly saving of \$27.7 per unit.

4.5.3 Diesel particulate filters

As discussed in the literature review, DPFs require significant maintenance and are costly to replace. An estimation of \$25,000 was made for the cost to retrofit a diesel loader with a DPF system, and a lifespan of 5,000 engine hours was assumed. This was accounted for as an ongoing consumable cost, at \$25000/5000hr = \$5 per operating hour. To reflect the additional maintenance costs required for inspection and cleaning, an extra \$2 per operating hour was included, and the availability was decreased from 85% to 83%.

The model gave a diesel hourly cost per unit of \$100.9, which equates to a saving of \$24.9 per operating hour per unit, slightly less than those predicted for biodiesel.

5. Discussion

5.1 Findings from the LCC model

The base case results were consistent with the initial expectation, and the general consensus from literature, that electric loaders can offer lower operating costs. The primary cause of this was found to be the potential savings in ventilation. In fact, if ventilation savings were not included in the model, the hourly cost per unit for eLHDs became \$127.8, \$2 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, and yet still were 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.

The effect of the fleet number and composition on hourly costs was quite complicated. The most important outcome was that 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 labour 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 main sensitivity, and changes of 10% were observed to change total hourly costs by around \$17. Due to increased possible ventilation savings, raising the ventilation system power actually had the effect of lowering hourly costs. Lowering electric vehicle 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/when power-dependent ventilation requirements are introduced for electric vehicles, how low this value is set will have major implications on the economic feasibility of electric machinery.

When energy costs were investigated, the results suggested that increases of 10c/L in diesel price caused rises in diesel vehicle hourly costs of around \$2.6 per unit. However, from the literature review, it was apparent that diesel fuel costs are likely to remain relatively stable in the short-term future. As far as electricity prices are concerned, increases of 1c/kWh actually decreased total costs by around \$4 per hour. 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.

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 viable in comparison to diesel units.

The two other alternatives modelled, biodiesel and diesel particulate filters, demonstrated hourly savings of around \$28 per unit and \$25 per unit respectively. These both used the assumption that, under WAMSIR 1995 regulation 10.52, sub-regulations 8 and 9, ventilation requirements could be reduced to $0.03m^3/s/kW$. This may be unlikely, however the assumption was made to provide a 'best case' scenario for diesel loaders. These savings result in an hourly cost of around \$100 per diesel unit, which is still around 15% more expensive than electric models. This is due to the higher power of diesel units, as well as the additional costs related to fuel consumption for biodiesel, and both consumables and maintenance for DPFs.

There are some other drawbacks of these other alternatives which must also be considered. Biodiesel can result in less power and therefore decreased productivity (EERE 2013). Furthermore, manufacturers may not allow biodiesel blends above a certain threshold (typically 5-20%), which may mean that DPM reductions are not as significant as predicted (EERE 2013). As discussed in the literature review, DPFs are designed to operate at an optimal air-fuel ratio, and require regular cleaning and inspection to ensure effective DPM filtration (Hedges et. al 2007). Consequently, if either the engine or DPF is not maintained, or if the filter unexpectedly fails, then employees may be exposed to higher quantities of exhaust fumes and DPM than are expected, and ventilation rates could be severely inadequate.

5.2 Limitations of the model

The first limitation of the LCC model is the relatively poor data quality used to make estimations for default inputs. Maintenance and consumable cost elements were largely based on figures from AUSIMM's 1st edition of the *Cost Estimation Handbook*, published back in 1993. Maintenance, which proved to be such an important factor in the LCC model, is dependent on a range of factors including operating conditions, mining methods, mine design and management strategies, and 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 air flow 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 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 the main economic driving force behind choosing electrical equipment in underground mines. While determining an appropriate ventilation requirement for electric vehicles may require further studies, this will certainly be significantly lower than the current diesel requirement of $0.05m^3/s/kW$.

The other assumption made was that variable speed drives are installed for primary fans. Eric Williams suggested that most primary fans are set to run at 0% or 100% (direct online), and that in order to fine-tune output flow rate, variable speed drives would be required. These drives come at a significant expense of around $150,000, which represents a 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 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 offence and $62,500 for subsequent offenses.

The cost relating to the relocation of electric loaders between haulage routes was not included into the model either, 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 (2010), for a large site where frequent relocation is required, a cost 10–20% of total operating costs should be factored in. Though 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 similar to the 'best case' predicted values for diesel LHDs fitted with DPFs or running on biodiesel.

5.3 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. Some of these relationships can be seen in Figure 5.1, which is a productivity curve for the electric loader (Sandvik LH514E) used in the LCC model.

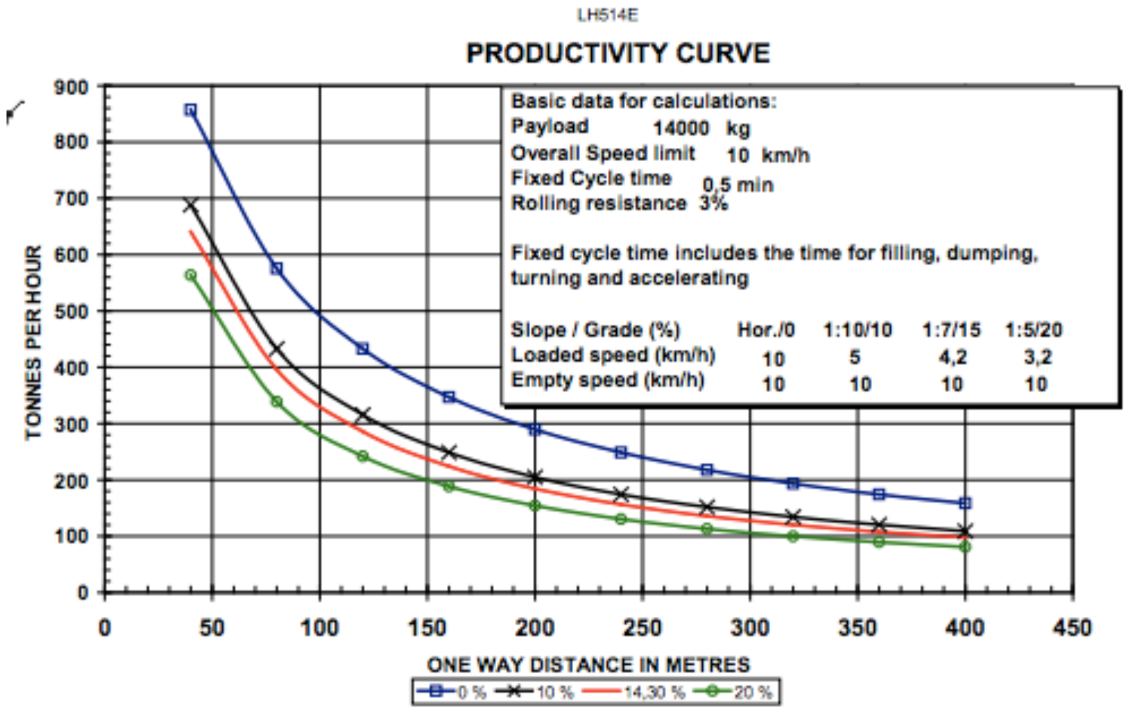

Figure 5.1: Productivity curve for Sandvik LH514E (Source: Sandvik 2010)

It can be seen from Figure 5.1 that 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, and 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.

Unfortunately, a similar graph could not be obtained for the diesel model (Sandvik LH514) for comparison. Furthermore, as mentioned in the literature review, there is no consensus among academics on the relative production rates of diesel and electric loaders. This is certainly an area which requires further research.

5.4 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 favour 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, which could in turn increase work efficiency.

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 & Knights (2012) suggest a maximum of 4 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. As alluded to in Section 5.2, 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 utilisation 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 (1992) suggests that this necessity to employ specific mine plans for effective use is one reason for the reluctance to embrace underground electrical equipment.

6. Conclusions & Future Work

Electric load haul dump units 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, especially 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 always had lower operating costs and hence a higher percentage of diesel units resulted in higher operating costs. Mines with large ventilation requirements make electric alternatives even 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 minimised. 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 minimising relocation costs. Paterson & Knights (2012) 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 ‘greenfields’ mining projects, rather than existing ‘brownfields’ mines.

Future comparative productivity trials are vital in definitively determining the economic feasibility of electric loaders. More studies aimed at quantifying both operating costs of loaders and ventilation requirements of electric vehicles are also necessary, due to the lack of published works 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 analysed, 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 MSHA 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 electric load haul dump units 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 serves as a solid base for future work, and provides (to the authors knowledge) the first *comprehensive* comparative study between electric and diesel load haul dump units in underground hard rock mines.

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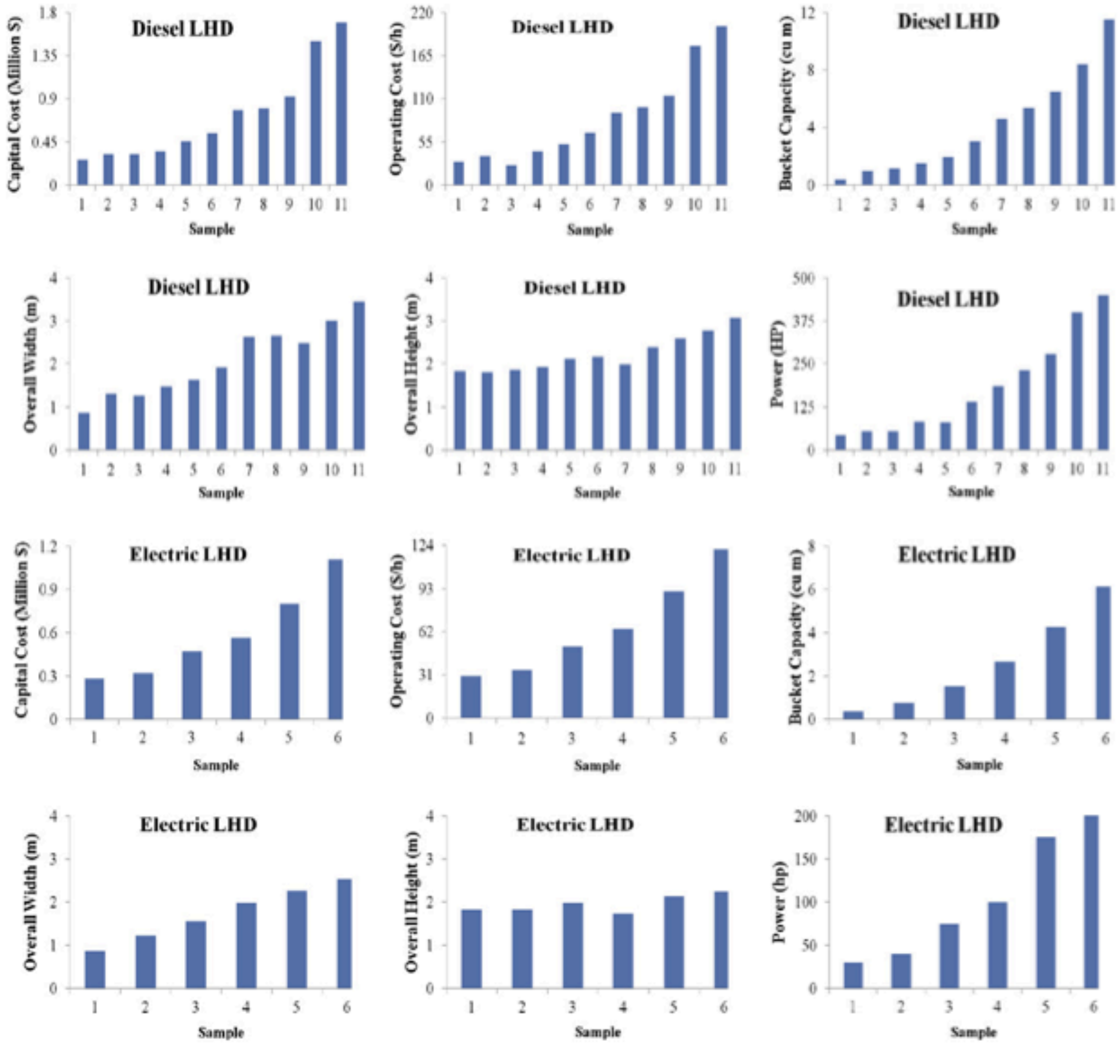
Appendix A – InfoMine USA Data (cited in Sayadi et al. 2012)



Appendix B: Additional diesel exhaust management methods

MSHA (2012)	MVSA (2012)	de la Vergne (2003)
– Minimize engine idling and lugging – Limit engine power – Keep fuel and lube oil clean – Keep heavy traffic downstream from miners who work outside of cabs (e.g. powder crew) – Route haul trucks in return air, especially when ascending ramps loaded – Utilize traffic control and production scheduling – Schedule blasters on non-load/haul shifts – Keep cab doors and windows closed	– Administrative controls (e.g. shift rotations) – Alternative haulage systems (e.g. conveyors) – Intake airways to reduce contamination of intake air – Changes to force ventilation systems in development heading to extract contaminated air to surface, rather than back through drives	– Electronic ignition to improve combustion efficiency – Engine replacement at 4,000 hours of service (expensive) – Allow accurate DPM readings (ban smoking in mines, replace rock drill oil with semi – solid grease) – Dust masks, respirators, etc. for miners

Appendix C – LCC model screenshots

Parameter	Units	Diesel	Electric
Fleet:			
Fleet number	-	4	4
Capital cost	AUS$/unit	1000000	1200000
Discount rate	%	9	
Fuel:			
Fuel cost	$/L	1.13	
Fuel consumption	L/hr	40	
Power of diesel engine/electric motor	kW	256	180
Electricity cost: grid or generator	$/kWh		0.2
Usage:			
Availability	%	85	80
Use of Availability	%	70	70
Consumables:			
Lubricants	$/hr/unit	8	5
Tyres	$/hr/unit	15	15
Filters	$/hr/unit	8	
Maintenance:			
Parts - Machine	$/hr/unit	70	50
Parts - Trailing cable	$/hr/unit		30
Labour	$/hr/unit	20	25
Ventilation:			
Ventilation requirement	m^3/s/kW	0.05	0.03
Primary fan power	kW	500	
Number of primary fans	-	2	
Flow rate in mine	m^3/s	200	
Adjustment factor for auxiliary fans	-	2	
Average daily operating hrs of vent system	hr/day	23.5	

Parameter	Units	Diesel	Electric
Utilisation	%	59.5	56
Daily usage	hrs	14.3	13.4
Daily fuel cost for fleet	$/day	2581.824	
Daily power consumption for fleet	kWh		9677
Daily power cost for fleet	$/day		1935
Daily consumables, maintenance costs for fleet	$/day	6911.52	6720
Vent requirement if fleet were all diesel	m^3/s	102.4	
Actual ventilation requirement	m^3/s	51.2	21.6
Total ventilation	m^3/s	72.8	
Ventilation volume saving	%	14.8	
Ventilation power saving	%	38.2	
Mine daily ventilation consumption	kWh/day	47000	
Mine daily ventilation cost	$/day	9400	
Potential daily vent savings by electrics	$/day		3586

Parameter	Units	Diesel	Electric
Annual operating costs for fleet	$/year	3465070.6	3159206
Annual operating cost per vehicle	$/year	866267.64	789802
Annual ventilation savings per vehicle	$/year	0	327257

DIESEL

Year	0	1	2	3	4	5	6	7	8	9	10
Capital cost	1000000										
Annual operating cost		866267.64	866267.64	866267.6	866267.64	866267.6	866267.6	866267.6	866267.6	866267.6	866267.6
Relative annual vent cost		0	0	0	0	0	0	0	0	0	0
Total cash flow	1000000	866267.64	866267.64	866267.6	866267.64	866267.6	866267.6	866267.6	866267.6	866267.6	866267.6
Discount factor	1.000	0.917	0.842	0.772	0.708	0.650	0.596	0.547	0.502	0.460	0.422
Present cost	1000000	794740.95	729120.14	668917.6	613685.836	563014.5	516527.1	473878.1	434750.5	398853.7	365920.8
Net present cost per vehicle after 10 years	**6559409**										
Operating hours	**52122**										
NPC10/hour/vehicle	**125.8**										

ELECTRIC

Year	0	1	2	3	4	5	6	7	8	9	10
Capital cost	1200000										
operating cost		789802	789802	789802	789802	789802	789802	789802	789802	789802	789802
Relative annual vent cost		-327257	-327257	-327257	-327257	-327257	-327257	-327257	-327257	-327257	-327257
Total cash flow	1200000	462544.42	462544.42	462544.4	462544.421	462544.4	462544.4	462544.4	462544.4	462544.4	462544.4
Discount factor	1.000	0.917	0.842	0.772	0.708	0.650	0.596	0.547	0.502	0.460	0.422
Present cost	1200000	424352.68	389314.39	357169.2	327678.129	300622.1	275800.1	253027.6	232135.4	212968.3	195383.8
Net present cost per vehicle after 10 years	**4168452**										
Operating hours	**49056**										
NPC10/hour/vehicle	**85.0**										