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Human Factors Methods to Design Safer Mobile Mining Equipment

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Abstract

The global mining industry experiences a relatively high rate of accidents, injuries and deaths. A large number of these incidents involve interactions between people and mining equipment. This thesis describes the application of human factors methods to different parts of the design lifecycle of mobile mining equipment with the aim of encouraging more widespread adoption of these techniques. Three research studies are presented here.

In the first study (Chapter 2), injury narrative data obtained from surface coal mines in Australia were examined for human factors design issues. The injury narratives were coded using a constant comparative method that allowed categories and codes to be identified. A number of issues emerged, including the location of the person on the equipment (eg access ways) and the tasks being performed (such as maintenance). Multivariable analysis in a visual diagram allowed greater and potentially more usable information to emerge. Three specific use cases showed the benefits of greater targeting for future investigation in different areas of the mining industry. Analysis of this type should be standard in incident analysis and the methods of recording incidents should be broadened to encourage richer narrative information to be collected to allow additional trends to emerge.

The second study (Chapter 3) documented the analysis of in-depth interviews using the Critical Decision Method (CDM) with mining equipment operators who had been involved in incidents. The research found that the CDM interview method was able to identify many issues not contained within the original incident reports. The insights provided through the use of CDM could also help target redesign interventions at mine site, especially linked to mobile equipment redesign. Useful insights were frequently obtained from drawing the incident on a whiteboard. The data from each of the CDM interviews were then placed on the decision ladder. The results revealed that operators were very frequently 'shortcutting' a full decision making process, indicating that design solutions which address the immediate environment of the operator could prove more effective than interventions like knowledge-based retraining. However, in a practical sense, the combining of CDM outputs with the

decision ladder did not offer substantially greater design solutions than may have been gained through other approaches.

Chapter 4 examined an in-cab proximity detection system installed at an underground gold mine. The goal of the system was to make drivers of haul trucks more aware of surrounding vehicles, assist decision making and, ultimately, prevent collisions. The research used a variety of human factors methods to examine the system usability, acceptance and effectiveness. The results of the evaluation identified deficiencies with the proximity detection system and other factors of the operating environment. These produced a number of recommendations. An investigation of a subsequent collision at the site verified many of the issues observed. Some of the interface design recommendations were consequently developed and implemented with positive operator acceptance. The application of human factors methods can lead to positive changes in the design of proximity detection systems and, more broadly, help develop effective mining technologies from a user-centred perspective.

In conclusion, the three studies described in this thesis have produced both practically useful benefits and a contribution to knowledge. The results will encourage more widespread adoption of such human factors techniques by both mining equipment users and designers.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications during candidature

Peer-reviewed journal articles

Burgess-Limerick, R., Joy, J., Cooke, T., & Horberry, T. (2012). EDEEP—An Innovative Process for Improving the Safety of Mining Equipment. *Minerals*, 2(4), 272-282.

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Expert Reviewed Research Reports

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Contributions by others to the thesis

The introductory and concluding chapters of the thesis, numbers 1 and 5 respectively, were completed by the candidate purely with editorial assistance and guidance from my supervisors.

Chapter 2, a review of injury narratives at surface mines, was inspired by papers written by the associate supervisor Professor Robin Burgess-Limerick. However all of the research was entirely independently except for editorial assistance by supervisors in the final drafts.

In chapter 3, the use of naturalistic decision making methods, the initial research was done in partnership with my primary supervisor Associate Professor Tim Horberry. Subsequently, the initial analysis was completed in partnership, from which we co-wrote a journal paper together. The literature review and the deeper analysis, including the application of the decision ladder, was done by the candidate with minor advisory assistance from his supervisors.

In chapter 4, the review of the proximity detection system, initial advice was provided by my supervisor Associate Professor Tim Horberry. He also helped set up the relationship with the partner mine site and apply one of the several tools - a usability checklist - to allow an independent comparison with data collected by the candidate. All of the other research and analysis was completed by the candidate unassisted except for guidance from his supervisors during writing.

Statement of parts of the thesis submitted to qualify for the award of another degree

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List of Abbreviations used in the thesis

CDM: Critical Decision Method

CMI: Coal Mines Insurance Pty Limited

CTA: Cognitive Task Analysis

CWA: Cognitive Work Analysis

EDEEP: EMESRT Design Evaluation for Equipment Procurement

EMESRT: Earth Moving Equipment Safety Round Table

ETBA: Energy Trace and Barrier Analysis

HFACS: Human Factors Analysis and Classification System

I-CAM: Incident Cause Analysis Method

LHD: Load-Haul-Dump

LV: Light Vehicle

NIOSH: National Institute for Occupational Health and Safety

NDM: Naturalistic Decision Making

NSW: New South Wales

MISHC: Minerals Industry Safety and Health Centre

OHS: Occupational Health and Safety

OMAT: Operability and Maintainability Analysis Technique

PtD: Prevention Through Design

RFID: Radio Frequency Identification

RPD: Recognition Primed Decision

StD: Safety through Design

Chapter 1

Introduction

Abstract

The mining industry experiences a relatively high rate of accidents, injuries and deaths. A significant proportion of these involve mobile equipment. Despite the success in improving safety in other industries, the take-up of human factors methods in mining has not been as strong and the published research is also relatively sparse. This thesis treats this gap as an opportunity and describes the application of multiple human factors techniques to identify potential improvements in the design of mobile mining equipment.

This chapter introduces the thesis. A review of the recent safety performance in mining and the involvement of mobile equipment is undertaken followed by a review of the history of human factors in mining. The concept of the asset lifecycle is introduced and the chapter concludes with an outline of the three case studies and their associated research questions which will form the bulk of this thesis.

1.1 Problem Statement

1.1.1 Safety Record in Mining

In spite of significant improvements over the past century, mining continues to be a hazardous industry with relatively high rates of accidents, injuries and deaths. For example, in Australia, 10 mining workers were killed in 2013 (Safework Australia, 2014). This represents an increased rate on the previous 5 years where 36 fatalities occurred which was already 70% higher than the national average (Safework Australia, 2014). This is for an industry that already had a fatality rate of ten times that of what is considered a 'safe' industry (Minerals Industry Safety and Health Centre, 2005). The National Institute for Occupational Health and Safety (NIOSH) reports that the United States of America has experienced similarly high fatality rates

in comparison to general private industry (National Institute for Occupational Health and Safety, 2008). On a more descriptive note the then CEO of iron ore division of BHP Billiton iron described the safety performance of his company and the industry as “abysmal” (Wallace, 2009).

On a more positive note, the rates of serious but non-fatal injuries does seem to be reducing in sophisticated mining industries. For example in a report by the Minerals Industry Safety and Health Centre (MISHC) in 2005 the Australian Mining Industry noted that though the frequency of Long Term Injuries was decreasing between 1994-2004 (Minerals Industry Safety and Health Centre, 2005). Since then reports by Safework Australia show a reduction, albeit at a slower rate (Safework Australia, 2014). Similar reductions in serious injuries have occurred in the USA (National Institute for Occupational Health and Safety 2008). Despite these reductions, the rate of serious injuries in mining remains high.

1.1.2 Contribution of Mobile Equipment to Mining Accidents

Mobile equipment used in mining has been implicated in a significant proportion of the industry’s incidents, injuries and fatalities. For example, in Australia 22% of all LTI’s in the mining industry were associated with mobile plant and transport (Burgess-Limerick and Steiner, 2006) and 46% of injuries in New South Walks underground mining were associated with equipment, most of this mobile (Burgess-Limerick and Steiner, 2011). NIOSH notes that in the U.S.A from 2003-2007 30.2% of mining fatalities and 9.6% of mining injuries were related to powered haulage (National Institute for Occupational Health and Safety, 2008). Furthermore, as the below charts indicate, those fatalities and injuries not classified as ‘powered haulage’ do not necessarily rule out the role of mobile equipment. It does appear that significant Occupational Health and Safety (OH&S) issues in mining relate to mobile equipment.

**Distribution of Occupational Fatalities by Accident Class
Surface Mining Locations, 2003-2007 (N=192)**
Excludes Office Employees; Data Source: MSHA

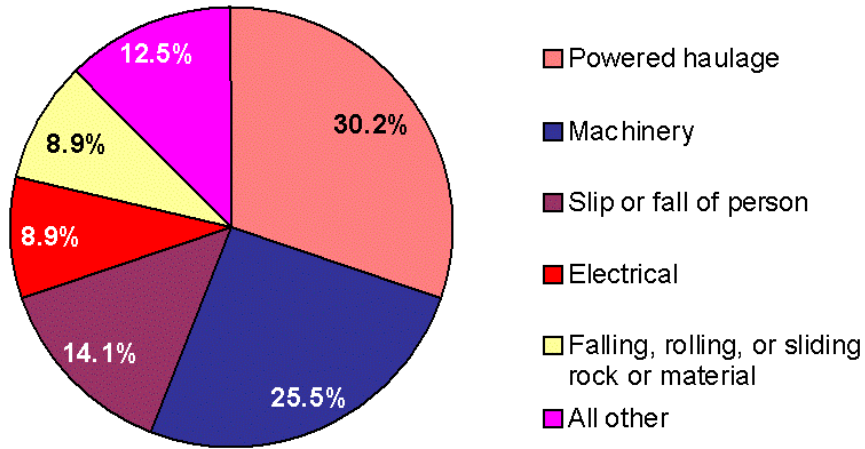


Figure 1.1: (National Institute for Occupational Health and Safety, 2008)

**Distribution of Lost-time Injuries by Accident Class
Surface Mining Locations, 2003-2007 (N=26,774)**
Excludes Office Employees; Data Source: MSHA

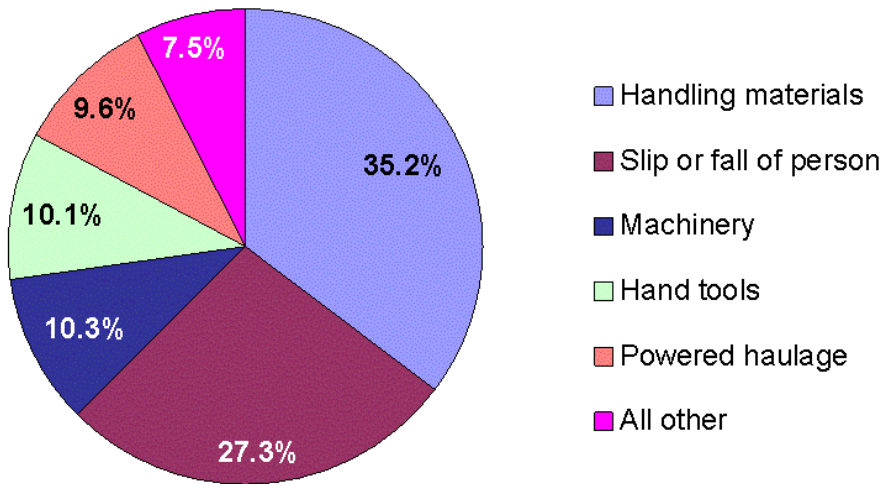


Figure 1.2: (National Institute for Occupational Health and Safety, 2008)

1.1.3 Transition from Technical to Human Causes

In the early part of the past century, mining fatalities were significantly related to technical and engineering limitations, with issues such as underground explosions or surface bench collapses predominating (Cooke and Horberry, 2010). Whilst these traditional major hazards still remain of concern, technological advances mean that the science for their control is largely understood. This changed the pattern of

mining accidents. When analysing the emerging pattern Simpson and Widdas found:

“an analysis of accidents over the past few years has not thrown up any uniquely mining aspect on which to concentrate... What is evident is that by far the most significant common element in current accident pattern is that of the human factor” (1992, p. 256).

This result is, perhaps, to be expected, as mining design engineers have a lower focus on human factors than other industries, including how the equipment is to be used by the operator and the sequence, importance and frequency of tasks/ functions (Sanders and Peay, 1988). Unfortunately, systematic attempts to address human factors problems in mining, especially preventatively, remain rare (Simpson, Horberry et al., 2009). Waterson and Klose (2010) suggested that this is potentially because of a persistent view that human factors is both common-sense, and costly. As noted above, the current approaches to injury prevention in mining seem to have had lessening effect on injury prevention and only been able to take fatalities to an uneasy plateau. Human factors methods could potentially be key to the next step change in safety performance of the minerals industry.

1.2 The Maturity of Human Factors in Mining

1.2.1 The History of Human Factors in Mining

The application of human factors in mining has been described as having a ‘rich but uneven history’ with much of the early research difficult or impossible to track down (Horberry, Burgess-Limerick et al., 2011). Much of this research was conducted at the tail end of the British Coal industry. These studies were often explanatory, but already indicate human factors issues related to design were at the core of remaining accidents. For example, a large review of various type of underground mining equipment found designed which inhibited safe and effective maintenance (Ferguson et. al., 1985). Another review found significant manual tasks risks involving moving unsteady equipment in cramped underground mines (Sims & Graveling, 1988). There were some trials of risk controls easily implemented at mine sites, such as increasing the strength of lights on mining caps to improve detection of

moving objects. (Martin & Graveling, 1983). Other attempts were made to systematically address human factors issues, such as the production of guidelines for the design of free-steered vehicles (Pethick & Mason, 1985) and better capturing human factors aspects in accident analysis and reporting (Graveling et. al., 1987)

However, since the collapse of the British Coal industry until relatively recently the published human factors research in mining was particularly sparse. During this era the examination of human factors in industries such as aviation, rail transport, petrochemical processing, road transport and nuclear power generation made significant advances. By contrast the implementation of human factors in mining has consistently come up against roadblocks, such as engineers believing they already know how people will act and that humans can be trained to overcome design related shortcomings (Dhillon, 2008).

This has left human factors in mining as a significantly less mature. Human factors has rarely been explicitly considered in the design of mining equipment. For example, Sanders and Peay (1988) reported in that mining design engineers rarely considered human factors including how the equipment is to be used by the operator including the sequence, importance and frequency of tasks/functions. Furthermore, they found the typical engineer does not systematically consider the interaction between human beings and equipment, has an over-reliance on old designs and a reluctance to modify these even with new information (Sanders and Peay, 1988). Although there are some indications that this is changing, the lack of consideration continues to the present day (eg. Wester & Burgess-Limerick, 2013).

1.2.2 Known contribution of Human Factors to Mining Accidents

Despite the widespread lack of maturity of human factors in mining, both there has been an increase in the reporting of human factors issues in mining accident investigations. For example Joy (2009) reported that 95% of investigations into serious bodily injuries had an element of active human error. Similarly, Sanders and Peay (1988) noted that an expert research panel found that 93% of underground mining accidents had a causal factor classified as perceptual-cognitive-motor error related to the more common term of human error.

Furthermore, there is some evidence that application of human factors methods can be successful in reducing injuries. For example, McPhee (2004) notes that the application of physical human factors significantly reduces the risk of musculoskeletal injuries through examination of equipment and task design. Some published research also shows that applied participative human factors approaches show promise in reducing musculoskeletal injuries (Burgess-Limerick, Straker et al., 2007; Torma-Krajewski et al., 2007). Although a variety of human factors methods show promise in improving safety there is potentially much more that could be gained from wider application of human factors techniques.

1.2.3 The Current Mindset in Mining Obstructs the Adoption of Human Factors

The lack of consideration of human factors methods in mining could stem from a widely-held belief that whilst human behaviour can be influenced by design, the major contributor to accidents is the erratic and unpredictable behaviour of unreliable people. This is what Dekker describes as the 'Bad Apple Theory' (Dekker, 2006). In this case extra training, improving procedures or reprimanding the person involved are likely to be considered appropriate and effective remedial actions as they are perceived to be the controls that target improving human reliability.

There is some evidence that this view is prevalent in the mining industry. In fact in one of the most recent and significant collections of human factors work in mining the authors begin with addressing myths about human error having its root causes in the front line by accident prone people (Simpson, Horberry et al., 2009). In a more specific example, Caterpillar, the world's largest manufacturer of mobile mining equipment, indicates a view that blames people for accidents, rather than considering the relationship to design. They state the following as the first sentence in all of their safety manuals for haul trucks:

*"Most accidents that involve product operation, maintenance and repair are caused by **failure** to observe **basic** safety rules or precautions. An accident can often be avoided by recognizing potentially hazardous situations before an accident occurs." (Caterpillar 2007; p.1 - emphasis added).*

Although mine sites are obviously much more constrained in making design changes than manufacturers, a focus on controlling personal failure appears prevalent. For example Rio Tinto Alcan found that 25% of their significant safety events in 2004 were related to Mobile Equipment (Laddychuk, 2008). However, by their own admission, they more frequently-used controls on the lower-end of the hierarchy of controls, such as training for pedestrians (administrative) and high visibility clothing (Personal Protective Equipment), and procedures for driver (administrative) (Laddychuk, 2008).

1.2.4 The Alternative Mindset that will help Human Factors Methods Flourish

The alternative view is that human performance is significantly related to context/ workplace design and is somewhat predictable. Dekker describes this as the 'New View' where accidents related to human factors can be related to the tools, tasks and other features of the operating environment (Dekker, 2006). It is arguable that the maturity of the mining industry has generally not reached the New View and the acceptance of human factors methods to improve equipment design lags behind other industries. Shutte recently stated that though there is growing awareness of the need for the application of human factors in mining, very little has been done about the application (Schutte, 2005). This is further hindered by a reactive rather than preventative risk management type of safety culture that is found to be persistent in mining (Bealko, Kovalchik et al., 2008). Mining will not move to the New View on rhetoric. It will only be through the successful application of methods that lead to changed designs and prevent errors and accidents.

1.2.5 Increasing human factors research in mining.

To say that mining should consider human factors more is a very broad statement. Human factors encompasses a huge number of issues and methods. It is not pragmatic to expect that the mining industry would accept an entire suite of methods quickly. Not only would it not be possible for an entire industry to quickly absorb such a large change, but the lack of success stories would support scepticism that change would bring benefit.

To a degree this scepticism is warranted. What is needed to propel human factors forwards in mining is a targeted and rigorous application of a variety of methods. The thesis will examine a number of methods involving human factors that could be used to examine and improve the safety, and in some cases reliability and productivity, of mobile mining equipment. This will build evidence to encourage more widespread application of human factors in the design of mining equipment.

1.3 Asset Lifecycle

The previous section suggests that the path forwards for improved safety in mining is through a greater focus on design especially related to mobile equipment. The next consideration is where, how and by whom does the design of mobile equipment actually occur. The answer to this question would be immediately obvious for most objects; the design happens prior to manufacture. If this were simply the case then the focus of any efforts should be with mobile equipment designers. However, because mining equipment is so complex and their environments of use so diverse it is not the case that the design of equipment simply finishes prior to manufacturing.

Design happens through modifications and adaptations throughout the equipment's life by a diverse range of people including the manufacturer, dealer and end user. Therefore, the opportunity to improve safety through design by applying mobile mining equipment exists across the entire life of the asset. Consequently, the research in this thesis has chosen to apply a number human factors method to key areas across the life of mobile equipment. As a whole, they will provide enhanced evidence and a framework of how industry can adopt human factors methods and promote safety through the design of mobile mining equipment.

1.3.1 Introduction to the Asset Lifecycle

The research in this thesis will apply multiple human factors techniques across the lifecycle mobile mining equipment. Before proceeding, it is worth defining what is meant by the lifecycle. All industrial equipment follows the process from the initial concept through until it is eventually disposed. This is commonly known as the Asset Lifecycle and will be defined here as it is by Horberry, Burgess-Limerick & Steiner (2010, see Figure 1.3)

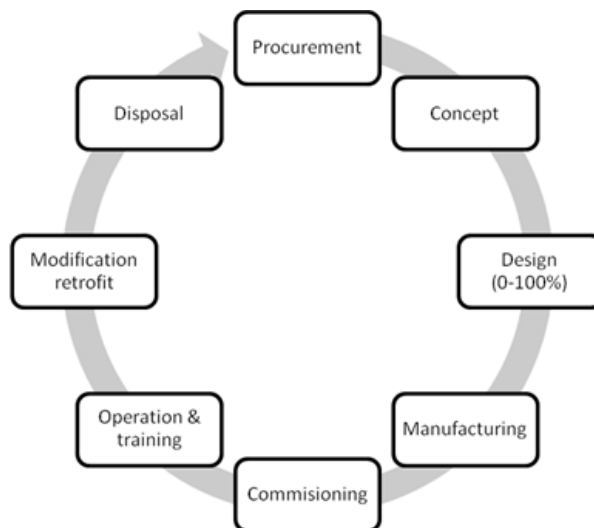


Figure 1.3: The Asset Lifecycle

1.3.2 Responsibility of Safety and the Asset Lifecycle

Historically, safety of equipment has been considered after the design and manufacturing was complete, probably beginning in the commissioning stage, with the responsibility primarily belonging to the asset owner (Everitt and Price, 2004). This has led to limited consideration of safety across the lifecycle of equipment, generally under a Job Safety Analysis or similar systems (Everitt and Price, 2004). Human factors knowledge has, traditionally, been applied following major incidents in the form of accident investigations. In fact the professional culture and language of human factors professionals often show more interest in analysis than design (Horberry, Burgess-Limerick et al., 2010). Whilst job safety and incident analysis is a valid endeavour, they do not easily describe how precursors to these incidents would be identified and designed-out in future (De Landre, Gibb et al., 2006).

A more recent perspective is to consider safety across the entire asset lifecycle. This perspective is theoretically linked to the Safety through Design (StD) and Prevention Through Design (PtD) initiatives (Howard, 2008). The primary changes to the historical approach is consideration of OH&S early in design stages and feeding back information learned about the use of previous models into future designs. As Sammarco et al stated:

“The key to safety is to “design in” safety early in the design by looking at the entire system, identifying hazards, designing to eliminate or reduce

hazards, and doing this over the system lifecycle” (Sammarco, Fisher et al. 2001, p.692)

This view is being reflected in changes to mining and safety regulation where designers are now given more duties and responsibility in relation to safety. For example the General Duty of Care provisions in Western Australian mining legislation state:

“Designers, manufacturers, importers and suppliers must ensure that the design and construction of any plant in a mine is, as far as is practicable, safe to install and use. To ensure the safety of any person who installs or operates the plant the designer, manufacturer, importer and supplier must reduce or prevent the possibility of exposing any person to hazards by identifying any hazards associated with the plant, assessing the risk of exposure of any person to that hazard and considering possible means of reducing the risk of exposure” (Department of Consumer and Employer Protection, 2006, p24).

Similar provisions exist in many other jurisdictions such as the Australian state of Queensland (The Queensland Government, 2009; and South Africa President's Office, 1996). This there is also some specific regulatory recognition of the responsibility for designers and manufacturers to consider human factors. For example, the Guideline for Mobile and Transportable Equipment for Use in Mines (MDG 15) produced by the mine safety regulator in the Australian state of New South Wales (NSW):

“All relevant ergonomic aspects of the equipment should be addressed by the Manufacturer in the design and manufacture of the equipment. A suitably qualified person should review the ergonomic aspects of the equipment to ensure compliance with good practice. A report should be prepared by this person and supplied to the Operator before delivery” (NSW Department of Primary Industries, 2002, p.14).

As in this instance ergonomics is analogous to human factors, the NSW regulator is essentially stating that a manufacturer should include a Human Factors Engineer in design and report on this to the mine site user. The recently published Core Body of Knowledge for OHS professionals support this view, finding that safe design happens best through the application of human factors methods within a participatory framework (Horberry et. al., 2014). The core body of knowledge also notes that the obligations of designers to understand equipment's context use and operating task to ensure safe design is more explicitly built into the model Work Health and Safety, which will cover all of Australia.

Additionally, there has been a slow move towards prosecuting manufacturers and designers of equipment. For example in the recent case of Authority of New South Wales (Inspector Mulder) v Arbor Products International in the New South Wales Industrial Relations Commission, found that the designer of a wood chipping equipment was culpable for the injuries to a person employed by the purchaser of their equipment with the judgement stating:

“The duty to provide a risk free work environment is a duty owed not only to the careful and observant employee but also to the hasty, careless, inadvertent, inattentive, unreasonable or disobedient employee in respect of conduct that is reasonably foreseeable” (Johnstone, 2003, p.58).

In a similar example an enforceable undertaking was reached with a mining company, and a manufacturing of mining equipment following a fatality related to a mobile roof-bolter (Department of Trade and Investment, 2008). The undertaking specified a 4 stage project which included identifying target area for focus and a resulting tool to review equipment. Both parties were 50% responsible for financing the undertaking. The resulting tool was incorporated into a Machine Design Guideline for roof bolting equipment with a heavy focus on human plant interaction, especially in the area of designing the control of the bolting system to prevent human error. This enforceable undertaking represents a move to both consider human factors methods necessary and the responsibility for safety being shared by the equipment manufacturers.

Therefore, there is now a more pressing requirement for the minerals industry to consider not only the safety of equipment when primarily under the control of the end user but also the elements under control of the manufacturer and designer. However, despite this imperative, there is little evidence that human factors is considered systematically throughout the lifecycle. In fact, it is thought that most engineers during manufacture and design will typically focus on technical issues, such as equipment reliability and payload, overlooking human factors concerns which are then typically passed from one phase to the next (Horberry, Burgess-Limerick et al., 2010). A simplified relationship of the role of the end user and manufacturer to the asset lifecycle is depicted in figure 1.4.

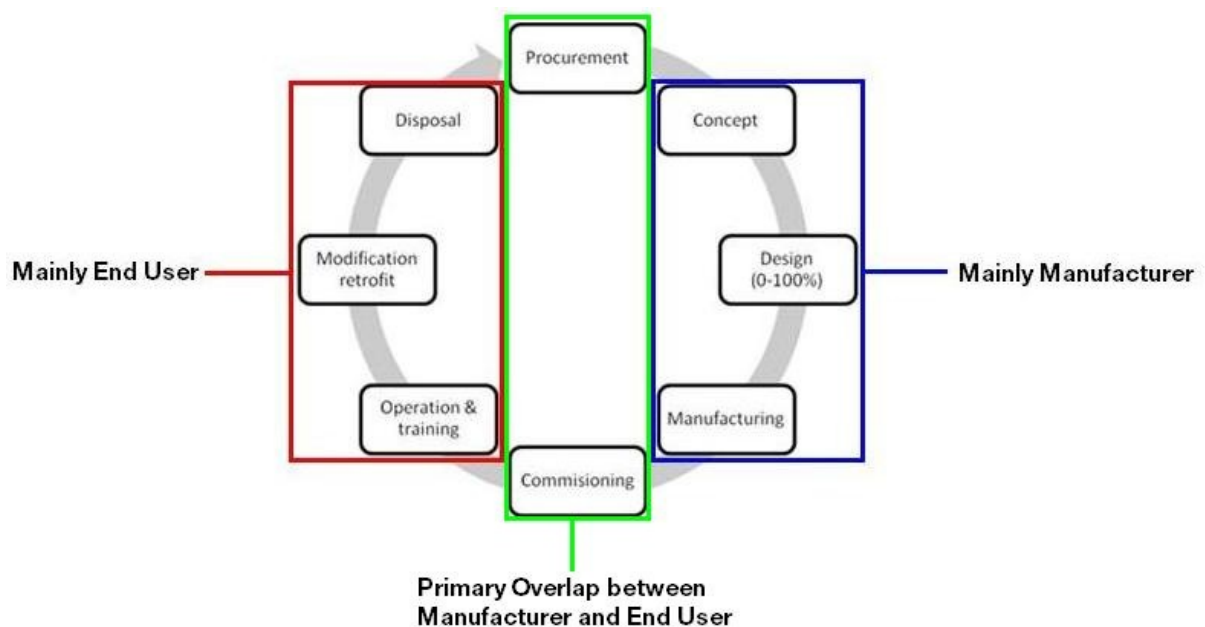


Figure 1.4: The relationship of the end-user and manufacturer in the asset lifecycle

1.3.3 Cost to Improve Safety and the Asset Lifecycle

This approach is noted to result in increased safety and productivity, through both cost reduction and direct productivity increases (Sammarco, Fisher et al., 2001). This fits well with general consensus among Human Factors professionals that the earlier they are involved in a design project the greater the potential benefit from an optimal design. This is because the ability to make changes becomes more constrained throughout the asset lifecycle (Marcus, 2005). The primary driver behind the reduction in the ease/ability to make changes later in the asset lifecycle is that as

significant design and development work has already taken place, and if serious human-system interface problems subsequently emerge the cost of changes and retro-fits is likely to be considerable (Hendrick, 2003). The cost of these changes or retrofits are regularly several orders of magnitude larger than if they had been made earlier in the Asset Lifecycle (MacLeod 2003; Gambatese, 2008).

Hendrick states claims that appropriate consideration of Human Factors consumes 1% of the design budget when brought in at the start of the project and 12% if brought in after the system is in operation (Hendrick, 2003). Figure 1.5, adapted from the lifecycle costing guideline published by NSW Treasury (2004), depicts this concept:

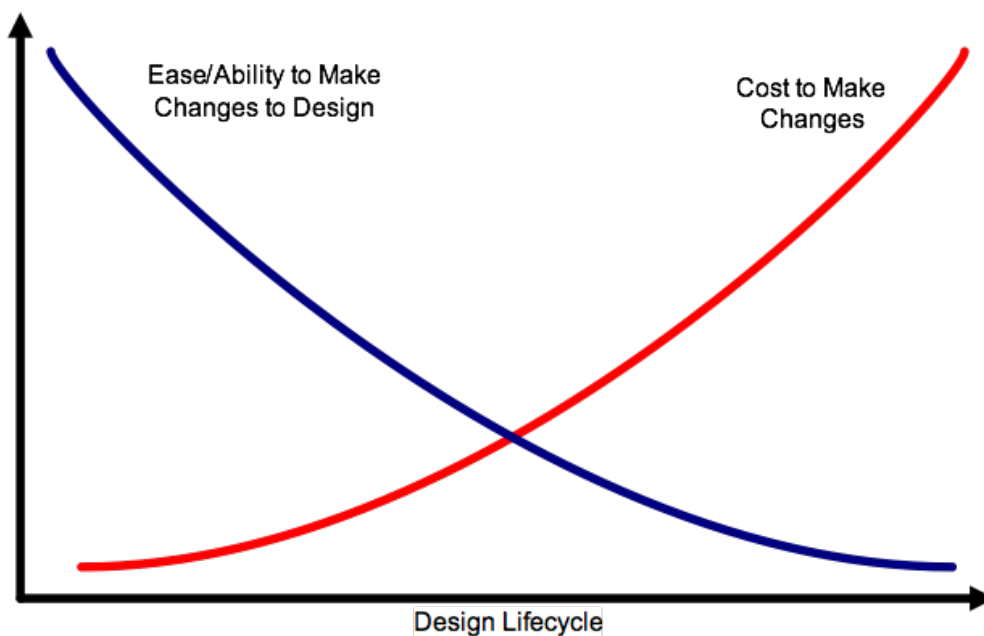


Figure 1.5: Ease and cost to make change across the asset lifecycle

Furthermore, a significant amount of the available projects funds are committed during the concept and design stages. Miles and Swift (1998) contend that this is up to 80% of the available funds. Therefore, if human factors is considered late in the design process, after strategic decisions have been made and resources committed, meaning that the cost to make any change will increase the required budget dramatically (Dul and Neumann, 2005). This implies that if human factors concerns are not explicitly considered early in the design of equipment it is unlikely that there will be funds available for changing designs and the product will enter the

marketplace with many flaws unchanged. Therefore, some human factors related changes later in the asset lifecycle are not just costly but financially impossible.

Certainly there is a feeling within the human factors community that often human factors professionals are not appropriately included in the early phases of design. Marsot (2005) described the problem well in the following quote:

“The inevitable problems that arise during these stages, combined with the difficulty or even absence of communication between the engineering specialists and those representing different disciplines such as ergonomics, can produce an adverse and/or unpredictable impact on satisfying such needs, especially those associated with occupational risk prevention. These needs are indeed often perceived as design constraints... and are consequently addressed only at the end of the design process through the adoption of remedial measures embodying compromises, which can subsequently turn out to contradict operational needs” (Marsot, 2005, p.186).

Therefore, when making changes to equipment later in the Asset Lifecycle only minor adaptations and corrections can be made and human factors is experienced as a time-consuming and costly activity. In such situations, the potential of ergonomics to contribute positively to the design is limited (Dul and Neumann, 2009). This would seem to indicate that the focus of human factors methods should be early in the Asset Lifecycle and primarily during the *concept* and *design* stages.

1.3.4 The Paradox of Human Factors and the Asset Lifecycle

Unfortunately, many factors not known during design, are important for clearly understanding the effect of human factors related interventions (MacLeod, 2003). As stated by Hale et al:

“Many safety related decisions depend on detailed knowledge about the design object; knowledge which is not available until the design has matured to a certain degree” (Hale, Kirwan et al., 2007, p. 311).

Furthermore, even once the design of the object is known there is still uncertainty about the context of use, such as the physical working environment, the skill and attitude of the persons involved and other work demands such as time pressure. Therefore, whilst effects of appropriate human factors changes earlier in the Asset Lifecycle can be both more effective and less costly, it is more difficult to accurately predict the eventual consequence at this stage (Hendrick, 2003). This has been labelled the 'paradox of design ergonomics' where accurate expression based on a work situation must wait until that situation is fully designed, yet by then it will be too late to intervene in its design (Marsot, 2005). This concept is shown in figure 1.6. Therefore, for complex pieces of equipment it is timely to consider safety across entire asset lifecycles, including into the next generations of equipment.

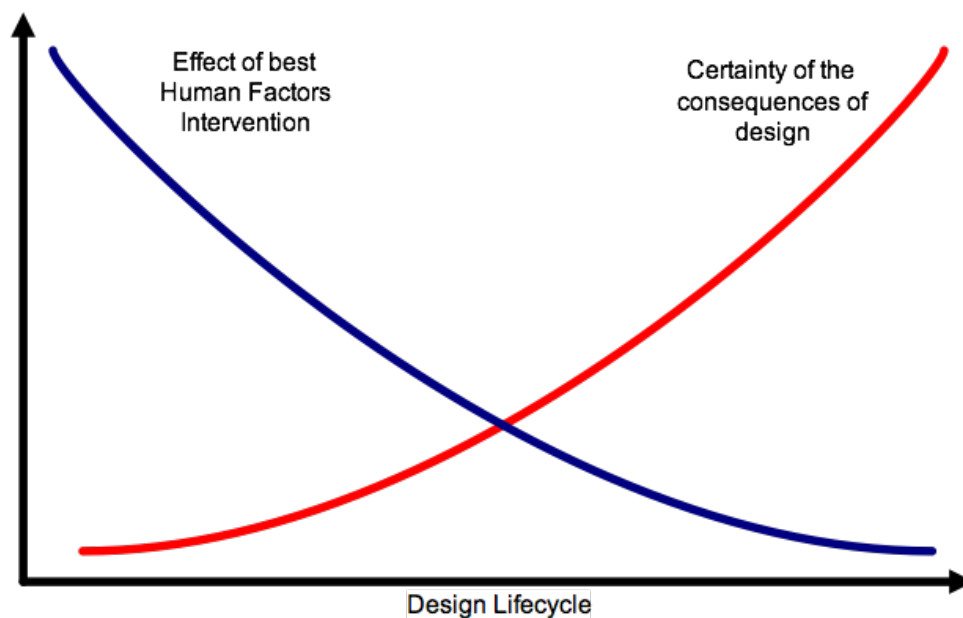


Figure 1.6: The certainty of consequences and effect changes across the asset lifecycle.

1.4 Research Questions

The broad focus of this thesis is the practical application of human factors in the mining industry. The goal is to learn about the effectiveness and acceptance of a variety of methods when applied to mobile mining equipment to help shape a future direction of human factors professionals working in the mining and, ultimately, deliver intrinsically safer equipment. In a practical sense this was done by the application of

a wide range of human factors methods in 3 case studies presented in individual chapters. Each of these case studies have specific research questions.

The research questions for Chapter 2 are:

1. What can be learnt about injuries associated with mobile mining equipment from recoding mining injury narratives with a focus of human tasks using the constant comparative method?
2. What is revealed by transforming the recoded injury narratives as a search tool with a graphical output for specific areas of focus?

The research questions for Chapter 3 are:

3. When the Critical Decision Method is used with mobile mining equipment operators what does it reveal about incidents that were previously unknown?
4. What is learnt by using The Decision Ladder to represent the cognitive process of mobile mining equipment operators at the time they were involved in an incident that can be used to make design recommendations?

The research questions for Chapter 4 are:

5. When human factors methods are applied to proximity detection systems in mobile mining equipment what design recommendations to prevent collisions emerge?
6. What can be learnt about the accuracy and effectiveness of design recommendations to prevent collisions at mines by investigating a real collision?
7. When design changes in a proximity detection system for mobile mining equipment based on human factors methods are implemented what can be learnt from investigating their acceptance by mobile mining equipment operators?

The above research questions represent the application of over a dozen human factors methods each already applied to either different domains or issues. The following sections will detail the thesis structure including the contents of each case study in more detail.

1.5 Thesis structure

The research presented in this thesis consists of three studies that employ diverse human factors methods to identify and improve the safe design of mobile mining equipment. Together, they show that a user-centred design approach can be beneficial at several different stages of the mining equipment. Figure 1.7 illustrates the overall thesis structure.

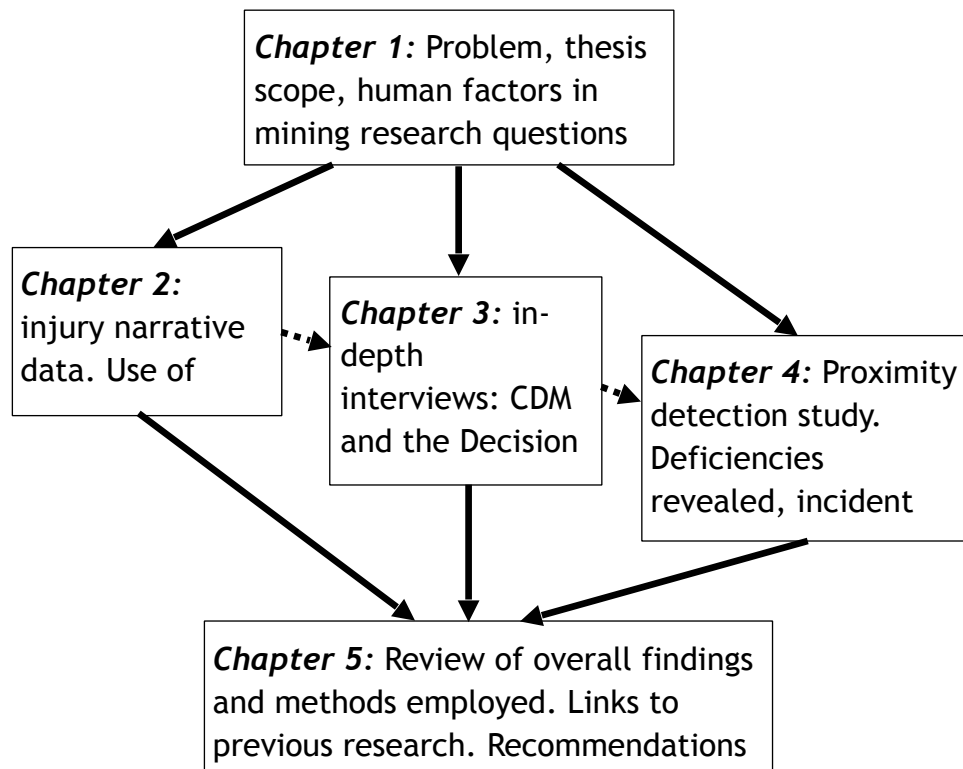


Figure 1.7: Thesis Structure

In Chapter 2, injury narrative data obtained from surface coal mines in Australia were examined for human factors issues that had not previously been coded or analysed, such as involvement of mobile equipment, type of equipment and task being performed. The codes for each category were built using the constant comparative method. These data were then presented using a graphical multivariable method. Together, the coding and visual representation showed that dominant human factors issues emerged with differing pieces of equipment, allowing targeted efforts to improve safety to occur. For example, equipment access and egress was frequently found to be an injury risk factor.

Chapter 3 documents the analysis of in-depth interviews with nine experienced mining equipment operators. The mining equipment operators were previously involved in mobile equipment incidents. The interviews used the Critical Decision Method (CDM). The subsequent analysis of the CDM data employed the use of a model of decision making called the Decision Ladder. These techniques were used to better understand the cognitive demands of operating mobile equipment in a complex mining environment. The chapter shows that both how these methods can give a deeper understanding of how mining operators make decisions, but also how the results of the incident investigations can easily be turned into specific and targeted design suggestions.

Chapter 4 details a multiple-method study of prototype in-vehicle proximity detection technology employed in Australian underground gold mine. The goal of the proximity detection systems was to give operator information about the surrounding equipment in an attempt to improve operator decision-making and thus prevent vehicle-to-vehicle collisions. A range of human factors methods were employed, including measurement of system constraints, usability audits, direct observations of operator behaviour, interviews and a survey regarding operator acceptance of the technology. The results identified deficiencies with the overall effectiveness of the prototype proximity detection system and other controls implemented to prevent collisions. An investigation of a subsequent collision at the mine site verified many of these revealed issues. Some of the recommendations for system improvement were deployed in a revised version of the proximity detection device: a subsequent evaluation involving drivers found the system changes to be positive.

Chapter 5 concludes the thesis. It summarises the results of the three studies, and how the obtained findings link to, and build on, previous research. A potential path forwards for human factors and equipment design is then described. This path may help future researchers to continue to progress human factors research and development work in mining. More specifically, contributions to knowledge obtained by applying diverse human factors methods in this thesis can point towards what types of methods and issues should be targeted to help improve the safe design of the next generations of mining equipment.

Chapter 2

Injury Narrative Analysis as Human Factors Tool

Abstract

Analysis of injury narrative data obtained from surface coal mines in Australia was undertaken using two complimentary methods. In the first method, the injury narratives were examined to look at a number of human factors issues that had not previously been coded, such as involvement of mobile equipment, type of equipment and task being performed. The codes for each category were built using the constant comparative method. Key results included that mobile equipment was associated with the majority of injuries in this domain; that the majority of injuries happened during operation; and that access/egress injuries were a significant issue.

The data were then presented using a graphical multivariable method that allows the dominant relationships to be visually identified in the resulting figures. The variables can be combined in various ways to accommodate different goals. Three perspectives were identified to assess the utility of the visual interrogation in identifying specific goals. In each case, issues could be identified which included task and environment related information. This included specific task and location patterns for access and egress, task and mechanism injury patterns during operation and priority patterns for a team of bulldozer designers.

The multivariable technique allows identification of operator-centred issues and consequently can be considered a useful human factors technique. It is likely that a more specific focus for further investigation will lead to improved effectiveness of interventions. A number of the issues identified are the subject of subsequent chapters.

2.1 Introduction

2.1.1 When Injuries are Routinely Recorded in Mining

While incidents resulting in serious consequences are subject to detailed investigation, the reporting of less serious injuries includes a one to two sentence description of the circumstances. This is referred to here as the injury narrative. Whilst the narratives are recorded and reported to government agencies and/or workers' compensation insurers, it is uncommon for any further analysis of the narratives to be undertaken (although see Burgess-Limerick, 2011 for exceptions). It may be that analysing injury narratives to categorise variables such as mobile equipment, task being performed, location of equipment and injury mechanism could assist in identifying specific user-centred equipment design changes. To examine this question, five years of injury narratives reported by Australian surface coal mines were analysed in this chapter. A number of analytical techniques were applied with the goal of allowing user centred interrogation following a data coding procedure.

2.1.2 Relationship to the Asset Lifecycle

The incident data obtained are, by definition, from equipment in operation. This means that the primary role of data analysis is to consider modifications to the design, operation and training in relation to current equipment. It also provides a secondary role, in feeding key issues with past designs into the concept and design of future equipment models (Moore, Porter et al, 2009). These roles and their relationship to the Asset Lifecycle can be seen in Figure 2.1:

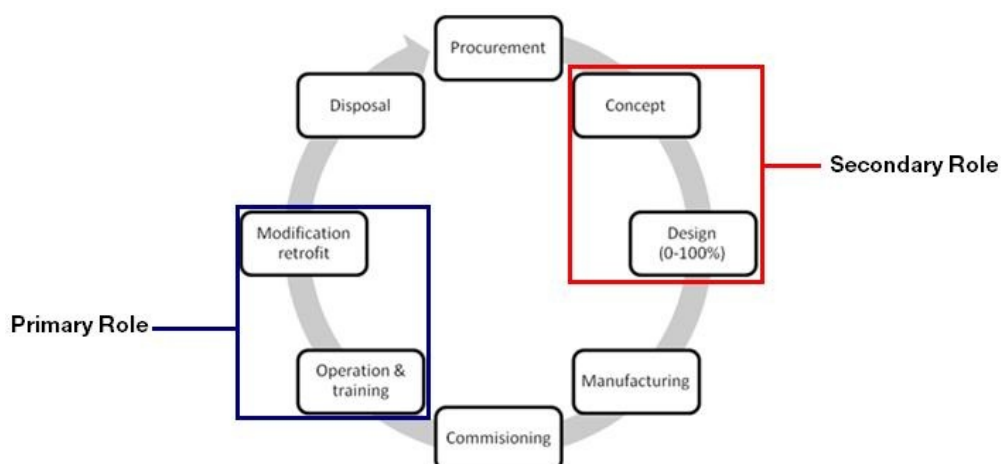


Figure 2.1: Relationship of the injury narrative analysis to the asset lifecycle

2.1.3 Reasons to Review Incident and Injury Data

2.1.3.1 User-Centred Classifications

The analysis of injury data reflects the goals of the analyst. In most industries this is usually an insurer interested in broad trends (Maiti and Bhattacharjee, 1999). This broad approach has commonly occurred in mining. For example, Maiti and Bhattacharjee's (1999) review of coal mining injuries looked at individual factors (age, experience and occupation) as well as broad factors (mine type and location within mine). Government agencies typically report trends over time (eg. lost time injuries to different body parts).

These analyses serve a purpose; however, they are not overly useful to those seeking to manage injury risks. Interventions based upon broad trends involve significant assumptions and guesswork, and their effectiveness almost impossible to determine (Salmon, Stanton et al., 2011). Instead, the identification of specific high risk sources of injuries would allow more effective intervention. A subsequent change in the narrative trends can also provide a measure the effectiveness of interventions. For example, changes to injury narrative trends were used to measure slip and fall injuries in hospitals due to a broad-scale intervention (Bell, Collins et al., 2008). Not only was the analysis able to determine the overall effectiveness of the program, but also the effect the program was having on different sources of falls, allowing future interventions to be targeted accordingly.

Despite the possible benefits, the classification of large quantities of data that includes human, equipment and environment interactions is under-utilised in occupational health and safety (Shephard, Kahler et al, 2000). Even studies that have specifically considered task factors can be too broad give a specific focus to further analysis and intervention. For example, Williamson et al coded the mechanism of occupational fatalities in Australia, New Zealand and the USA but were only able to give broad areas of focus such as 'electrocution' in Australia or 'drowning' in New Zealand (Williamson, Feyer et al., 2001). Focusing on an industry is likely to give a more useful result.

The injury narratives reported by mining companies typically provide sufficient detail to determine the equipment involved, location of person on the equipment, task being performed, and mechanism of injury. These represent three components of the cycle of human factors: namely equipment, task and unsuccessful performance (Wickens, Lee et al., 2003). The cycle of human factors is shown in Figure 2.2 with the components where it is anticipated that more information can be gained from reviewing the injury narratives underlined.

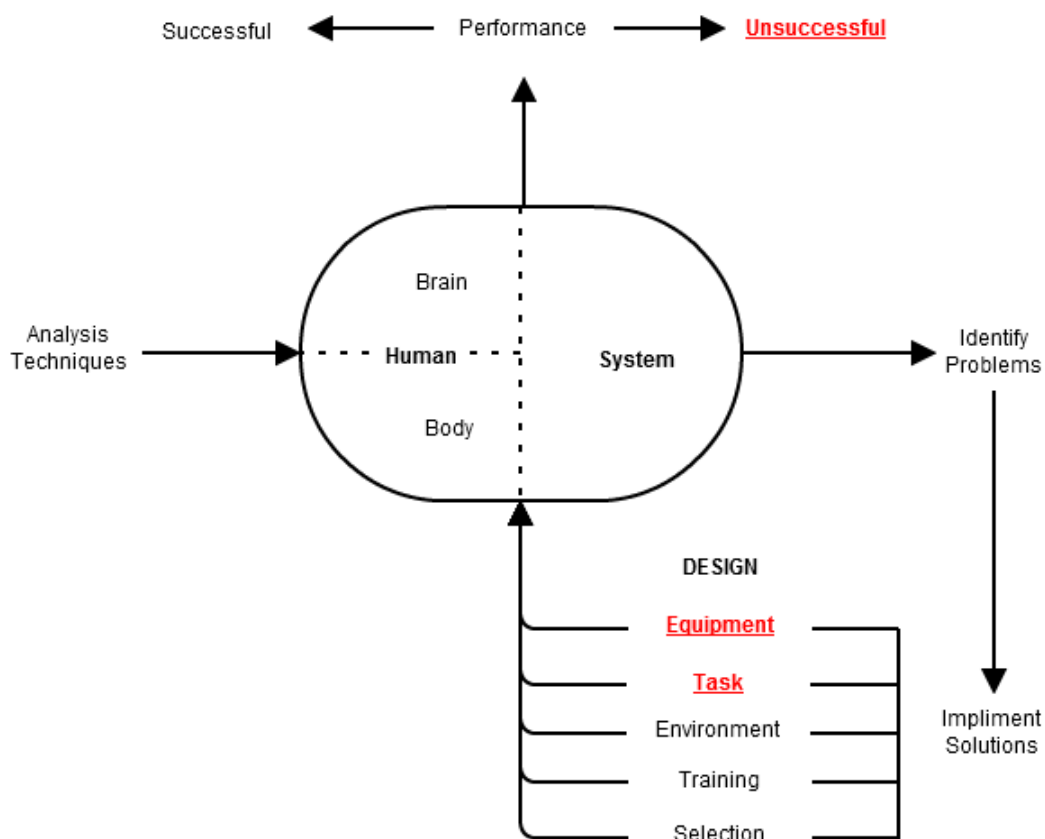


Figure 2.2: The Cycle of Human Factors with the elements available in the injury narratives highlighted– Adapted from Wickens, Lee et al. (2003)

2.1.3.2 Target Further Analysis with Hazard Patterns

From the above it can be seen that many elements of the lifecycle cannot be drawn from the narratives. In fact, the elements within human and system usually require application of specialist analytical techniques. Therefore, it is unlikely that problems and solutions can be confidently and fully determined without further analysis. However, it may be that by including analysis of narratives with the components of





the cycle of human factors that are available, it would be possible to focus the application of other techniques. For example, if the narratives can target a location on a piece of equipment where a mechanism of injury commonly occurs within a particular task, any further analysis that does occur can be highly targeted and efficient. Others have successfully achieved similar user-centred insights by reviewing the originally recorded text before it is hidden by a coding system (Lincoln, Sorock et al., 2004).

There are some examples of injury narrative analysis in mining that have provided useful results. For example, Helander et al (1983) conducted a review of underground hard rock mining injuries adding previously unclassified elements, such as machine part and body part involved, and this analysis was successful in highlighting specific issues requiring priority attention (Helander, Krohn et al., 1983). Randolph and Bolt (1997) were similarly able to identify issues of priority in surface haulage accidents. However, not all the user-centred categories were considered in any of the previous reviews. Additionally, the analyses that do exist in surface mining are now dated and not specific to Australia. The injury profile that remains may be different, especially considering western mining injury rates have fallen significantly over the last decade and a half, especially in Australia (Poplin, Miller et al., 2008). For these reasons it is timely to review the injury data in surface coal mining to determine if previously identified issues remain a priority or if other trends are emerging.

Some of the most useful information comes from being able to layer multiple levels of information to create more specific hazard scenarios. Drury and Brill (1983) described these as 'hazard patterns', combining elements of the person, product, environment and task, and claimed the interrelationship of these factors means this type of review became a useful human factors method. Although this technique is under-utilised, it has been used to successfully in various high hazard occupational environments such as military transport (Lincoln, Sorock et al., 2004), civil construction (Bondy, Lipscomb et al., 2005) and farming (Bunn, Slavova et al., 2008). Table 2.1 shows a visualisation of how adding multiple, user-centred, layers when considering surface mining equipment can draw the focus for further analysis;

in this case falling from a side platform. The extra layers make it obvious that if injuries are occurring in this area, changing the fall protection method appears an obvious solution.

Table 2.1: Example of how layering categories focuses on a hazard pattern

1 Layer	2 Layers	3 Layers	4 Layers
Equipment: Haul Truck	Equipment: Haul Truck	Equipment: Haul Truck	Equipment: Haul Truck
	Location: Platforms/ Decks	Location: Platforms/ Decks	Location: Platforms/ Decks
		Task: Cleaning	Task: Cleaning
			Mechanism: Slip/Trip
			

There are some recent reviews that looked for ‘hazard patterns’ on underground coal mining equipment. Burgess Limerick (2011) identified specific priority issues by combining equipment type, injury mechanism and activity being undertaken. For example, cable handling on bolters / continuous miners is significantly associated with strain injuries. Additionally, infrequent but potentially high consequence events were also identified. Most of these were around mobile mining equipment contacting people. Burgess-Limerick & Steiner (2006) have found similar utility and results related to underground coal mining equipment in an earlier Australian Study (2006) and in the USA (2007). Figure 2.3 shows how Burgess-Limerick et al previously layered data to reveal ‘hazard patterns’.

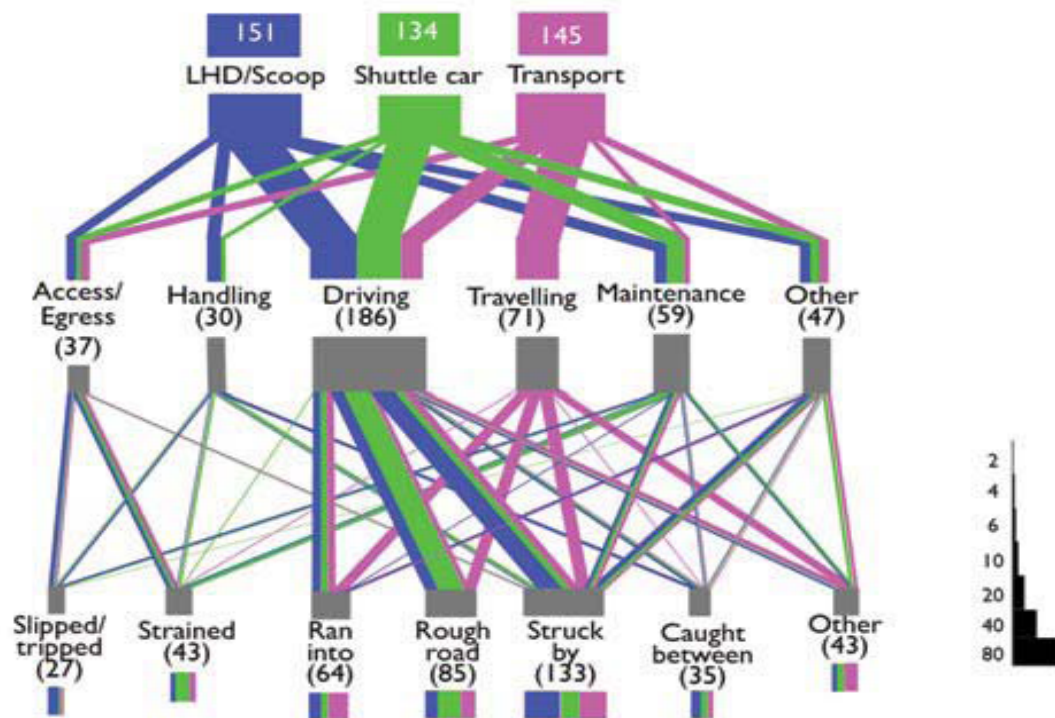


Figure 2.3: Hazard Patterns in Underground Mining Equipment

There may even be hints in some of the narratives about what human factors methods or design changes could be trialled. For example, Steiner and Burgess-Limerick (2006) found that a significant cause of roof or rib bolting accidents came from ‘caught between’ injuries which, in turn, *could* be associated with the design of the operator controls. This information could be used to inform immediate modification on existing equipment such as, for example, guarding controls from inadvertent operation, or redesigning controls to reduce the probability of selection or direction errors. These findings prompted subsequent research to examine the effect of different variables in the design roof bolting controls, such as coding, spacing and directional compatibility, and mitigating control measures (Steiner, Burgess-Limerick et al, 2013)

2.1.3.3 Determine if Access and Egress Remains a Priority Issue

Previous investigations related to mining have found that getting into position to perform a work task (access) or exiting the area of a task performance (egress) has been associated with injuries. For example, Moore, Porter & Dempsey (2009) found that in the calendar years 2006 and 2007 nearly half of the injuries recorded in the

Mine Safety and Health Administration (USA) were associated with access/egress. The majority of these were associated with mobile mining equipment and approximately three quarters during egress. This has been a continuing issue for the mining industry. For example, Randolph and Boldt (1997) found that in the USA mining industry from 1989-1991 more than a quarter of all accidents were associated with access/egress: more than all injuries associated with maintenance tasks.

Therefore, it would seem likely that access/egress would be associated with mobile mining equipment injuries within the narrative. However, in recent years access and egress from mobile equipment has received considerable attention from the industry. Some have noted that this attention is manifesting in design changes to the equipment:

“Manufacturers have provided better walkways, handrails, and no-slip surfaces. Manufacturers have also improved access points for maintenance tasks that can now often be done at ground level. Some mines are even starting to put aftermarket stairs on their equipment. However, problems still exist with access around the cab (cleaning windows) and to maintenance areas (changing filters).” (Moore, Porter et al, 2009, p.4).

It is likely that at least some these design changes have caused a drop in the risks associated with access and egress. This may have resulted in a decrease in injury rates, to the point where it is no longer a priority issue. There appears to be some preliminary indication that a drop may have occurred with one study in the USA showing raw access and egress injury rates in 1988-1997 more than twice as high as study that reviewed rates in 2006-2007 (Wiehagen & Jaspal, 2001; Moore, Porter et al., 2009). Whilst the methods for the two studies differ, such a large change could provide an indication that the circumstances may have altered.

2.1.4 Limitation of Injury Narrative Analysis

Analysis of incident and injury reports has limitations that should be noted.

2.1.4.1 Omissions and Inaccuracy in Data Recording

There is no guarantee that the person who wrote the narrative was in full possession of the facts or did not make an error. For example, an injured person must correctly recall the event and feel motivated to report it accurately. Commonly the injured person may tell the story to a third party, such as a safety officer or shift manager, who may misinterpret the employee's story. Even when the narrative is accurate, key information may be omitted or vague because the recorder was required to make a judgement about what information is important to record (Randolph & Boldt, 1997). Kletz (2009) found that injury narratives were usually accurate in their description of the immediate event; however, the causal information provided was inaccurate and incomplete, potentially leading to multiple interpretations. The possibility of this occurring in the injury narratives used is increased due to their general brevity and general lack of industry knowledge of human factors issues related to design.

Primary causes/sources of accidents have been included in other injury narrative analysis (Lincoln, Sorock et al., 2004; Patterson & Shappell, 2010). If detailed reports were to be analysed, such as fatality reports, it might be possible to use human error classification tools such as Human Factors Analysis and Classification System (HFACS) coding system (Patterson, 2008) or Incident Cause Analysis Method (I-CAM). The application of HFACS in relation to serious incident in mining has shown, unsurprisingly, that various human factor issues were evident. This includes organisational influences, unsafe supervision, preconditions for unsafe acts and, eventually, the unsafe acts themselves (Patterson, 2008; Patterson & Shappell, 2010; Salmon, Stanton et al., 2011).

However, in shorter injury narratives there is usually not enough information to determine a primary source or cause. It is also an oversimplification to state a single cause and it is often impossible to separate human performance limitation and a design that 'forced' or 'promoted' an error (Randolph, 1997; Dekker, 2006). Instead,

the analysis focussed on information, such as task being performed and equipment type, which is unlikely to be omitted or entered in error.

Additionally, whilst the application of HFACS in mining has provided evidence that human factors methods would likely be useful when applied to appropriate issues, it provides limited guidance as to where equipment design initiatives should be targeted. The proposed countermeasures in this regard are noted to be general, with the only recommendation specifically noting equipment stating 'evaluation/ redesign of equipment prone to violations' (Salmon, Stanton et al., 2011). In contrast, the classification of the user-centred information, as is proposed here, is likely to allow issues of priority for deeper analysis to emerge. The appropriate method can then be matched with the issue, leading to recommendations targeted at direct causes and, ultimately, equipment design improvements with a greater chance of success.

2.1.4.2 Overall Trends only Determine Frequency

Another limitation is that, due to the detail involved, the method can only look at the overall frequency of hazard patterns without adjusting for the exposure or potential consequence. Whilst knowing the overall frequency of incidents can be useful, this does not indicate the true risk associated with a specific occupational task (Lincoln, Sorock et al., 2004). Burgess-Limerick found that in his injury narrative analysis it was necessary to individually highlight infrequent events that have an obviously high potential consequence, such as fatality or permanent serious injury because they would be hidden by only considering incident frequency (Burgess-Limerick, 2011).

However, this does not mean that the frequently occurring incidents associated with frequently occurring situations are less valid. On the contrary, the incidents are occurring frequently and can be considered a priority. Rather, it means that ignoring other major potential issues, simply because of their low frequency in relationship to historical injuries, is not valid. Therefore, this method can only highlight some priority issues and not unequivocally rule out others from investigation.

2.2 Aim

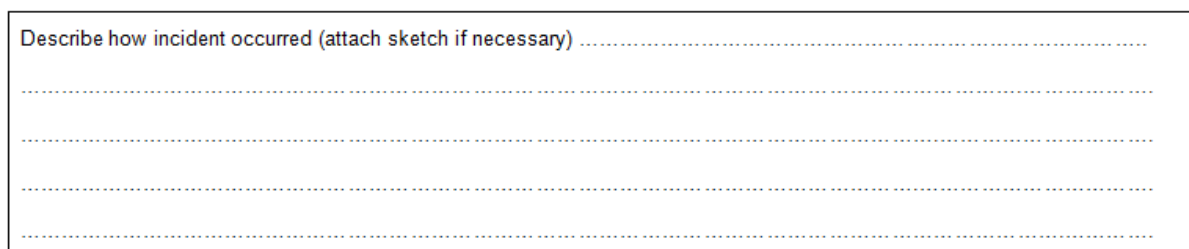
The primary aim of this chapter is to identify specific human factors issues that warrant further analysis. In the following chapters some of the identified issues will be analysed using alternative methods that lead to design deficiencies being identified and addressed through redesign. The secondary aim of this chapter is to reveal that exploration of more specific incident-related information, by combining multiple variables, allows tends to emerge that both allow specific identification of issues for future analysis and cater for a variety of perspectives.

2.3 Method

2.3.1 Dataset

The dataset obtained for analysis was open cut injury narratives between financial years from 2005-2009 provided to Coal Services Pty Ltd (Coal Service), the sole worker's compensation insurance provider to the New South Wales (NSW) Coal Industry. NSW is an Australian state which produces approximately 200 Million tonnes of coal a year which is approximately half of Australia's coal production (NSW Minerals Council Ltd, 2012).

All coal industry employees in NSW must have workers compensation insurance cover from Coal Mines Insurance Pty Limited (CMI), a subsidiary of Coal Services. If a worker sustains an injury, the employer must notify CMI within 48 hours by submitting an accident/incident form. On the form the employer is asked to "describe how the incident occurred" providing space for a short description of approximately 1 to 2 sentences. The box provided on the form is shown in Figure 2.5:



Describe how incident occurred (attach sketch if necessary)
.....
.....
.....
.....

Figure 2.4: Box for the employer's description of injury provided to the insurer.

The dataset is comprised of the employer's response to the above question within the 5 year timeframe of analysis. The only other available data were the date of registration, presumably with 48 hours of the injury occurrence, and whether the injury resulted in time lost from work. Table 2.2 shows a sample of incidents taken from the beginning of the 2008-2009 financial year:

Table 2.2: Illustrative example from the dataset of injury narratives

Date Registered	Time Lost	Incident Description
1/07/2008	N	DRIVING 930E DUMP TRUCK ON HAUL ROAD WHEN HE DROVE OVER A SOFT SPOT. HIS SEAT BOUNCED AND HE FELT A STRAIN TO HIS LEFT KNEE.
1/07/2008	N	HE WAS SETTING UP A STEERING Y PIECE WHEN FITTING STEERING PIN HE WAS TAPPING IT INTO PLACE WITH A HAMMER AND A FRAGMENT FLEW OFF AND LODGED IN HIS NOSE - PUNCTURE WOUND
1/07/2008	N	WHILE HE WAS OPERATING WHEEL LOADER ON COAL ROM HE STRAINED HIS NECK
1/07/2008	N	HE WAS OPERATING GRADER ON ROADS FOR HALF DAY AND AT END OF SHIFT HE STRAINED HIS RIGHT SHOULDER.
1/07/2008	N	WHILE WELDING IN A RESTRICTED AREA BENDING OVER IN A TWISTED AREA FOR A PERIOD OF TIME HE STRAINED HIS LOWER BACK
2/07/2008	Y	WHEN HE WAS CLIMBING DOWN LADDER ON REAR DUMP TRUCK, HE STEPPED OFF THE LADDER AND ROLLED HIS RIGHT ANKLE ON UNEVEN GROUND, CAUSING A SPRAIN TO HIS LEFT ANKLE.
2/07/2008	Y	HE WAS CLEANING TOP OF A DILUTE SUMP WITH A HIGH PRESSURE HOSE AND PLACED THE ONSE ON HAND RAIL. HE WAS STEPPING DOWN THE LADER WHEN HIS FOOT SLIPPED ON THE RUNG, STRAINING HIS RIGHT SHOULDER.
2/07/2008	Y	WHEN HE STEPPED OUT OF THE VEHICLE HE WAS TRAVELLING IN HE TWISTED HIS L/KNEE ON LOOSE GRAVEL - STRAIN
2/07/2008	Y	HE WAS RIDING HIS MOTORCYCLE TO WORK WHEN A LARGE KANGAROO JUMPED OUT OF LONG GRASS INTO HIS PATHWAY HE HIT THE KANGAROO CAUSING A SUPERFICIAL LACERATION TO HIS RIGHT KNEE

2.3.2 Data Classification Procedure

This is the first data analysis of this type in surface mining, and consequently neither the categories nor the options within the categories existed at the beginning of the analysis. The constant comparative method was used to develop the coding strategy (Glaser, 1965). Rather than beginning with a theory, data are collected and marked with a series of codes (Boeije, 2002). These codes are grouped into categories which can be used to create a hypothesis (Ragin, 1989).

From a review of the narratives it was determined that information could be extracted in seven user-centred categories grouped under the headings of equipment, task and accident, as is shown in Figure 2.6. Those under 'equipment' and 'task' represent extra information with the equipment and task design elements of the human factors performance cycle (Wickens, Lee et al., 2003). The elements under 'accident' represent extra information related to the unsuccessful performance element of the cycle (see Figure 2.2 for the cycle).

Equipment	Task	Accident
1 Type of Equipment	3 Activity Category	5 Body Part Injured
2 Location on Equipment	4 Task being Performed	6 Injury Mechanism
		7 Lost Time

Figure 2.5: Categories considered in review under appropriate element of the human factors performance cycle

The first code was a screening question asking if mobile mining equipment was involved (see Table 2.3). Injury narratives that did not relate to mobile equipment were discarded from subsequent analysis. Injuries related to travel to or from work were also identified and discarded.

Table 2.3: Screening question for relevance to the scope of inquiry

SCREENING QUESTION	
Was mobile mining equipment involved?	
Yes	No
Travel to or from work	Not Specified

Under each category, a number of codes – answers to the question posed – were developed and iteratively refined. This required re-checking the data on multiple occasions. In the creation of the codes the author had to be mindful that they were specific enough to be useful in focusing attention on particular issues, but not so specific that trends could not emerge. A flowchart of the coding process is shown in Figure 2.7.

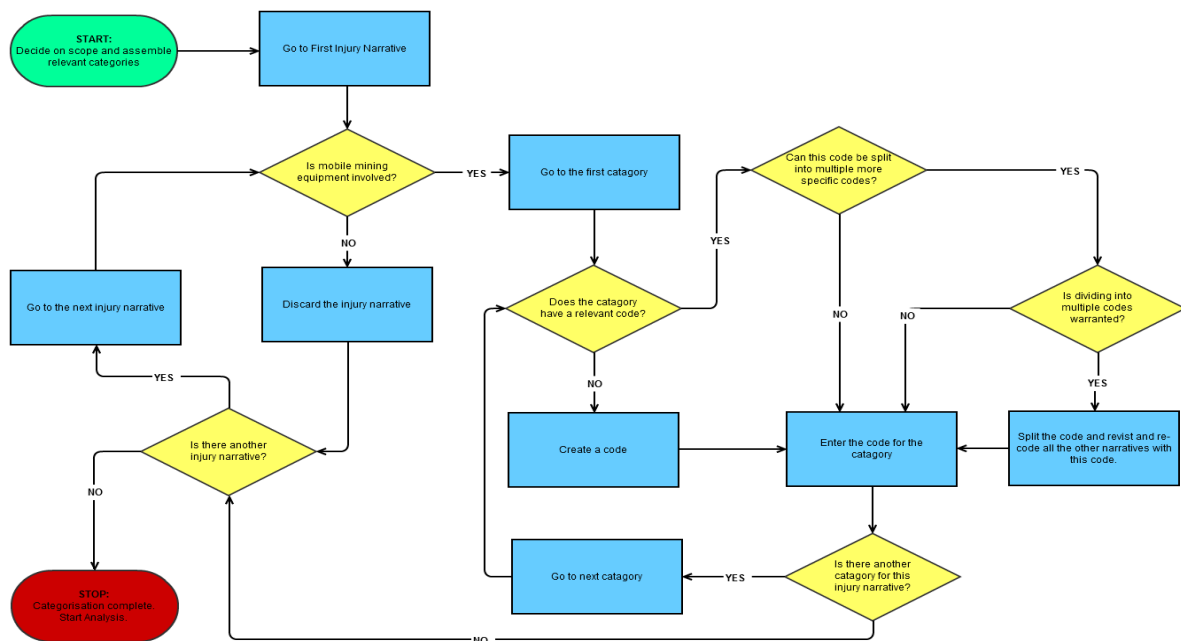


Figure 2.6: Flowchart of how user-centred categories for injury narratives were considered including iterative changes to codes

The following is the full list of categories and final codes used in the categorisation of the injury narratives:

1: Type of Equipment

What type of equipment was involved?

Haul Truck	Bulldozer
Grader/Scraper	Water Truck
Light Vehicles (Troup Carriers, Utes, etc)	Wheel Loader
Truck (not haul – smaller)	Dragline
Drill	Excavator
Other	Unknown

CATEGORY2: Location on Equipment

Where was the person positioned on the equipment?

Not Specified	Other
Operator Cabin	Platforms/Decks/Operational Controls/Mirrors
Ladder Access	Stair Access
Doorway	Unspecified or Implied Point Operational Access/Egress
Engine/Filters/Engine Covers/Brakes	Chains/Slings/Ropes
Bucket/Blade/Supports/Trusses/Masts	Cables/Hoses
Tyres/Wheels	Trailer / Tray
On Tracks	

CATEGORY 3: Activity Category

What Category of task?

- Operation
- Maintenance
- Access/Egress

CATEGORY 4: Task being Performed*What task was the person performing?*

Driving or General Operation	Driving – Reverse
Loading / Being Loaded	Dumping
Grading/Digging/Shovelling	Access
Egress	Access/Egress (not specified which)
Control Operation	Repair
Filling (eg Oil, Fuel, Liquids)	Part Removal or Installation
Inspection	Cleaning
Lifting	Unknown

CATEGORY 5: Body Part Injured*What body part was most significantly injured?*

Head – Face	Head – Other
Lower Arm (elbow, forearm, wrist, hand)	Upper Arm (Including shoulder)
Lower Leg (including foot)	Knee
Upper Leg (Including hip and thigh)	Lower back (Lumbar)
Upper Back (Thoracic)	Torso – Not back
Neck (Cervical)	Lungs / Respiratory System
Psychological	Other

CATEGORY 6: Injury Mechanism

What was the mechanism of injury?

Hit Rock Driving	Hit Pothole/Roadway Issue Driving
Rock or Excessive Load Dropped into Tray or on Headboard	Contact with other Mobile Equipment
Struck By	Bump Into
Overexertion	Slip/Trip
Strained	Caught between
Electrocuted	Dust or small foreign body
Burn	Loss of vehicle control – Whole vehicle
Loss of vehicle control – Part vehicle	Hard surface digging jarring vehicle
Unknown	

CATEGORY 7: Lost Time

Did the injury result in Lost time?

- Yes
- No

2.3.3 Single Variable Analysis

The categories, without combination, allow some initial questions to be answered that can generally help prioritise further investigations. Six basic questions were asked using a single category and dividing the category into a pie chart of codes. It was anticipated this could determine some broad trends, some of which are user-centred, which might warrant increased focus. The questions, and the justification of asking them, are given below.

Q1. Does mobile mining equipment warrant priority investigation? If so, what type(s) of equipment is highest priority?

Making changes to mobile mining equipment, and its context of operation, can be extremely time-consuming and costly for a mine. Therefore, for the topic of this thesis to be a valid line of investigation, logically it must first be shown that mobile mining equipment is significantly associated with injuries in mining.

There is a variety of mobile mining equipment used on site to perform different tasks associated with drilling, loading and transporting soil and ore. Each type of equipment has a distinct design and associated tasks. Whilst issues may be similar, solutions are not immediately transferable. Therefore, it would seem prudent to determine if any categories of equipment are worthy of priority, based on the injury narrative analysis.

Q2. Does the relationship between lost time injuries and mobile mining equipment support investigating it as a priority?

Of course, the above question can only help determine that mobile mining equipment appears heavily involved in accident. It does not state anything about the seriousness of the accidents involving and not involving mobile mining equipment. Furthermore, as the narratives are submitted around the time claimed, they cannot point to the long term prognosis of any injuries. Therefore, from the injury narratives it is difficult to determine absolute severity of injury.

However, there is one raw measure included that could be indicative of the severity of accidents: whether the injury required time off work or whether the worker was able to continue at work. Therefore, by dividing the narratives into those associated, or not associated, with mobile mining equipment and then comparing the percentage of incidents that resulted in lost time in each category, the narrative will give some indication of the relative severity of the injury. If mobile mining equipment has a comparable or higher rate of lost time injuries, then this is some indication that the severity of injuries warrants its inclusion.

Q.3 Does a person's location on the equipment indicate any areas of priority investigation?

The location on a particular piece of equipment is a category not regularly recorded in injury narrative analysis. However, in the majority of cases in the narrative, the location can be determined directly or inferred. By adding location on equipment to the analysis, the focus on specific design aspects is tightened. If particular, if parts of equipment are related to trends, then they can be further examined.

Q.4 Do some tasks or mechanisms warrant priority review?

Generally, the task being performed has been unclassified in analysis of injuries. The injury narratives appeared likely to identify a task that was being performed during injury. Additionally, the individual tasks could be further classified into their broad association with operations, maintenance or access/egress. If specific tasks emerge in each of these categories, they can be identified as warranting more scrutiny. The more traditionally recorded mechanism of injury is still valid to review, and determine, if any mechanisms occur more commonly than others.

Q.5 Does the location of injury on the body give priority areas to investigate?

In the majority of injury narratives the location on a person's body has been identified. This is an example of a factor that, on its own does not reveal useful information to an equipment designer or manager. For example, it might allow a person to determine that "mobile mining equipment is most commonly associated with back and hand injuries". Whilst this is only a theoretical example it does show how, on its own, this information could lead a user to broad based initiatives, such as manual handling training for back injuries and glove wearing policies for hand injuries. However, without more knowledge about the cause of these injuries the effectiveness of such programs is, at best, a guess.

Rather, body location information is much more useful in combination with other variables. For example, if information about *task* and *injury mechanism* is combined with the body part information, then the investigator would start to have useful information which could target some specific issues more likely to lead to design related interventions.

Q.6 Does access/egress remain a priority issue to address?

As noted above, previous analysis data in mining had determined that access and egress is a significant issue related to mining equipment. This has resulted in various training, awareness and design strategies. Both due to the time, and the potential for design changes to fundamentally change the tasks related to access and egress, historical data cannot be relied upon. Therefore, if access and egress

remains an issue, this review should give some indication that access and egress still warrant further analysis and elevate attention.

2.3.4 Narrative Multivariable Analysis

The above basic methods, however useful, can only give a rather broad focus. Other applications using less-task based but none-the-less similar approaches have not given any specific issue where further investigation or design solutions would be warranted (Kecojevic & Radomsky, 2004; Kecojevic, Komlijenovic et al., 2007). Others have found that *combining* factors in injury narrative analysis can reveal more specific issues to address than when they are considered alone (Burgess-Limerick, 2011). In fact, of the many models of human factors, all stress that it is the combination of a number of factors that affects real world performance. As was noted above, the seven codes come from three different levels of the human factors performance cycle. By including this level of detail, especially information about task, mechanism and location, the data can be manipulated to specific perspectives and associated investigatory goals.

A multivariable analysis will be undertaken to reveal emergent trends. In order demonstrate how the technique could be used, the multivariate analysis will take a perspective of key roles in the mining industry and follow a narrative as the data are examined. Whilst the persons are fictionalised, they do represent an actual perspective/role in the mining industry. Therefore, the lines of inquiry are realistic and possible. The persons are:

- A. *A Safety Officer* charged with reducing the risk and number of access/egress related injuries at surface mines through targeted initiatives.
- B. *A Mine Manager* at a typical mine searching for some specific initiatives to target for improved safety of mobile equipment.
- C. *A Lead Design Engineer for a manufacturer of bulldozers* who wants to learn specific areas where current designs could be improved in next generation bulldozers.

With seven categories, there is a number of ways to combine the variables. In this case the method was to first *constrain* the list of injury narratives by the selection of a

code within a category. For example, the Lead Design Engineer would only be interested in injury narratives associated with bulldozers. Then, within the constrained narratives, two categories are selected for comparison.

This comparison was done by mapping using Circos; a graphical presentation tool which was originally designed to visualise similarities and differences in genomes (Krzywinski, Schein et al., 2009). It uses a circular layout with interconnecting ribbons between two sets of codes. Each set of codes is given half of the outside of the circle. The area of each code around the outside of the circle represents its relative size. A ribbon connects two codes in different categories with the thickness of the ribbon representing the relative size of the relationship. How the chart is constructed is shown in Figure 2.7.

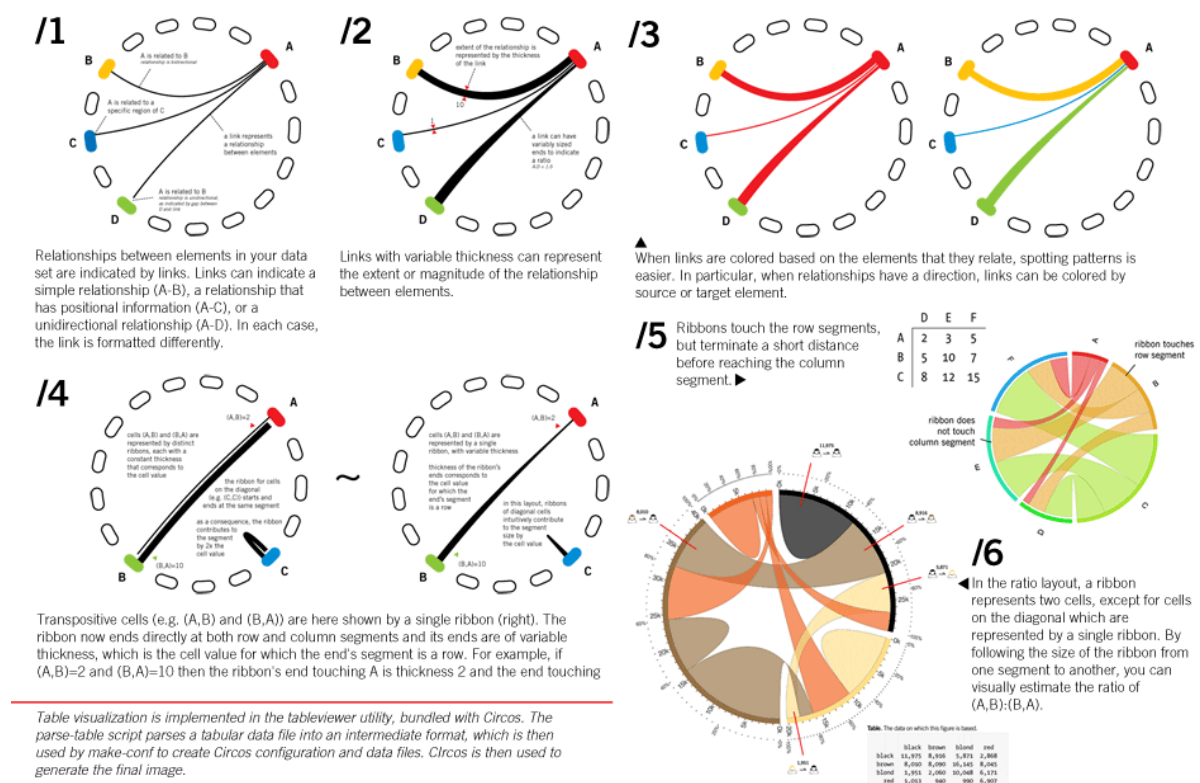


Figure 2.7: How a Circos graph is constructed (Krzywinski, 2011).

The resulting figure displays a number of pie charts in the one image, allowing them to be compared immediately and relatively. Whilst the tool is only visual, certain relationships appear larger and are therefore immediately obvious (Krzywinski, Schein et al., 2009). Larger visual relationships were selected and interpreted to

determine specific focus for further analysis. If successful, it shows how multiple layers of injury narrative trends can be explored graphically and target future analysis. This transfers from simply a reporting of broad trends into a human factors investigatory tool that can be used in field and participatory settings.

2.4 Results: Basic Questions

2.4.1 Does Mobile Mining Equipment warrant priority investigation? If so, what type(s) of equipment is highest priority?

There were 1,965 injuries claims registered with Coal Services in the five year period. Of these, at least 1,112 were associated with mobile mining equipment. Of these, 210 claims were registered for industrial deafness. Though industrial deafness could be associated with mobile mining equipment, and in fact is likely for those with a long history in mining, it can rarely be attributed to a specific incident (major explosions excepted). Therefore, these claims have been discarded in the total. Additionally, 132 of the claims involved travel to or from work and were discarded.

This leaves approximately two thirds (67.7%) of injuries at NSW surface coal mines in the period which were definitely associated with the operation or maintenance of mobile mining equipment at the mine site. 3.8% of injuries are possibly related to mobile mining equipment, but insufficient information has been provided to definitely include them in the count. This leaves only 28.5% of injuries which were definitely not associated with mobile mining equipment. Therefore, these raw numbers are supportive of investigating mobile mining equipment as the key area to improve safety in surface coal mining.

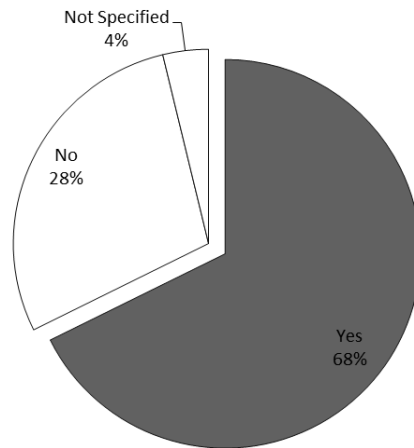


Figure 2.8: The involvement of Mobile Mining Equipment in recorded injuries after excluding injuries during travel to an from work.

The breakdown of equipment type is shown in the figure 2.9. Haul trucks (31.7%) and bulldozers (20.8%) make up slightly over half of the injuries logged. The other 8 vehicle types range from 8.0% at largest (graders/scrapers) to 2.7% at the smallest (excavators). This does not mean that other equipment types are not worth investigating. Rather, it indicates that, without any other knowledge about the prevalence of equipment as sites, investigating bulldozers and haul trucks as a priority would be justified. This is logical as haul trucks and bulldozers are the most common pieces of equipment used onsite. The bulk of this thesis has involved analysing haul trucks and bulldozers with some analysis of various other types of equipment including wheel loaders, drills, graders, light vehicles and excavators.

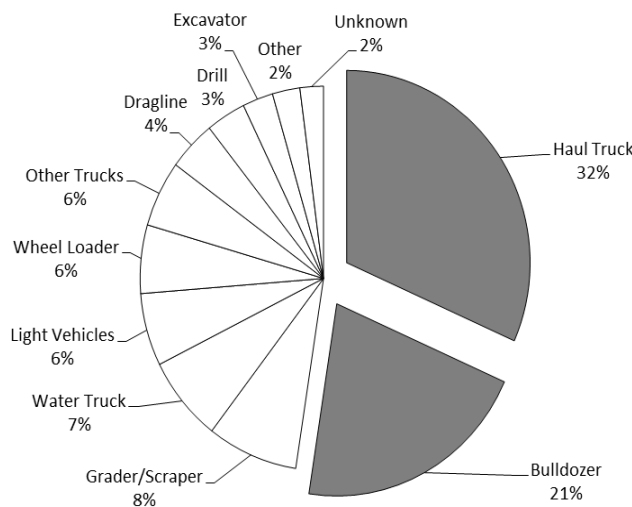


Figure 2.9: Injuries associated with different types of Mobile Mining Equipment

2.4.2 Does the relationship between lost time injuries and Mobile Mining Equipment support investigating it as a priority?

The ratio of lost time injuries to non-lost time injuries for claims associated or *not* associated with mobile mining equipment are almost identical. Whilst this measure is fairly blunt, it gives no indication that the injuries associated with mobile mining equipment are more or less severe as other injuries. This does not weaken the case for focusing on mobile mining equipment related injuries.

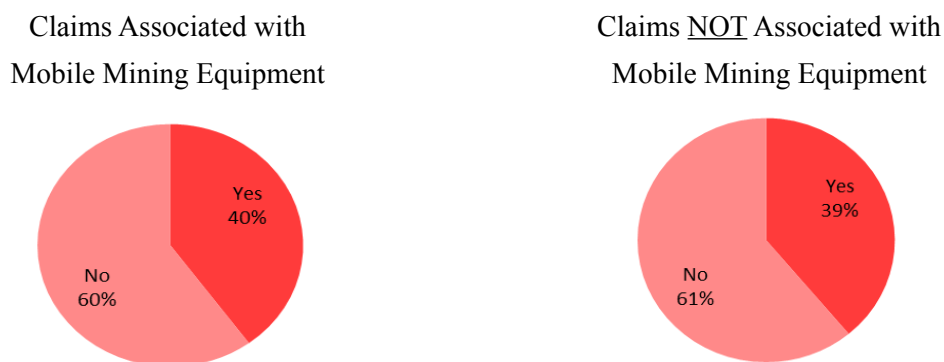


Figure 2.10: Was the claim a Lost Time Injury?

2.4.3 Does a person's location on equipment indicate any areas of priority investigation?

The first and most obvious note is that nearly half the injuries occurred when the injured person was in the operator's cabin. Because it is rare for maintenance tasks to occur in the cabin, it may be inferred that a significant proportion of injuries occur during the operation of equipment. This is shown in Figure 2.11. Some information is revealed when considering only those injuries outside the operator's cabin. Figure 2.12 illustrates the proportions of all other locations when the operator's cabin is excluded. The darker shading indicates areas design for access and egress that would be required for operations but also used commonly in maintenance. The light shading indicates areas accessed for maintenance where it is less common to have designed access and egress points on the equipment. The white are points that do not fit into these categories.

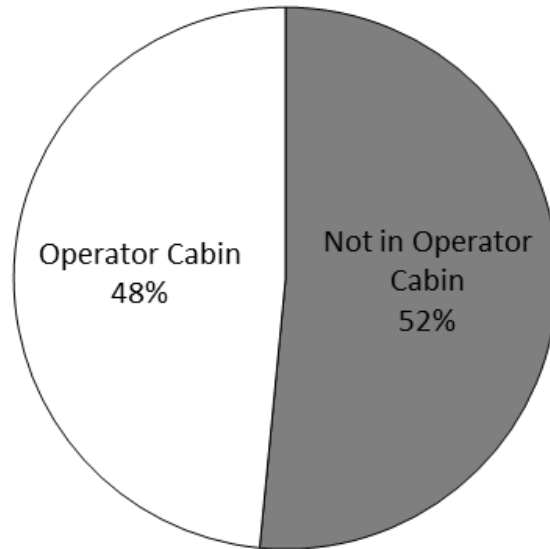


Figure 2.11: Injuries in Relation to Operator's Cabin

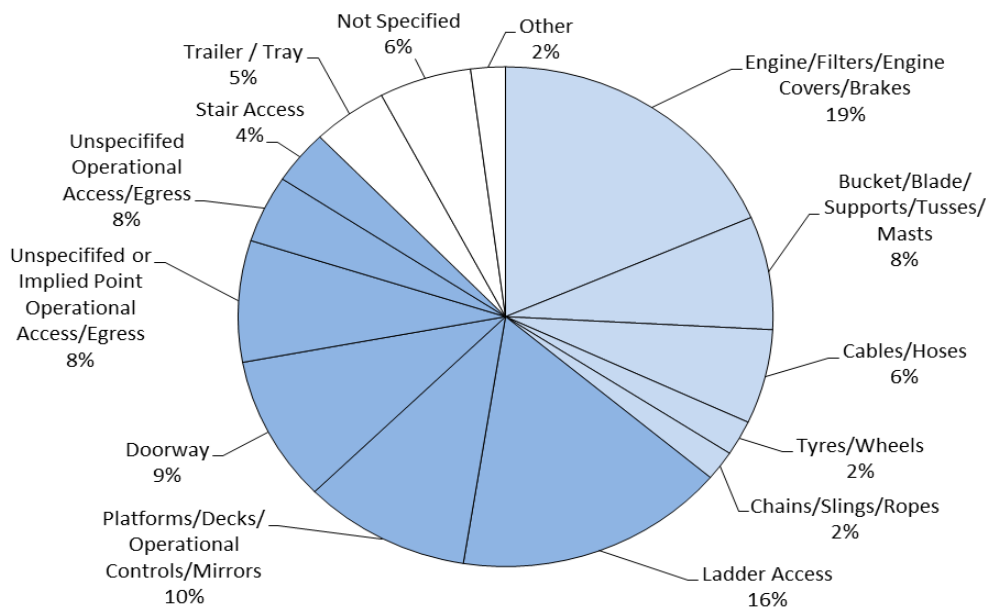


Figure 2.12: Injuries for all vehicle locations other than operator's cabin

One clear result is the seemingly high number of injuries on ladders as opposed to stairs. This difference is interesting as ladders and stairs of industrial equipment are usually listed under the same code (Rautiainen, Ledolter et al., 2009; Copley, Burnham et al., 2010) even though the tasks involving ladders have been highlighted a large cause of injury in previous studies (Moore, Porter et al., 2009). It is difficult to determine if this is just the prevalence of stairs compared to ladders. However, ladders have been previously determined as relatively riskier than stairs on mining

equipment based upon injury rates and time spent in the locations (Albin, Adams et al., 1990).

It is for this reason that in recent times many forms of mobile mining equipment, especially haul trucks, have changed from access via ladders to access via stairs. On the surface this would appear to be indicative that this is warranted and investigating ladders and stairways is a justified focus. When considering maintenance tasks those associated with the engine are heavily represented (19%). However, the reality is that the tasks and mechanisms across different types of equipment are so varied in this area that, on its own, neither this nor any other maintenance code give a good indication of where to focus further analysis.

2.4.4 Do some tasks or mechanisms to warrant priority review?

The mechanism of injury was also determined for each of the narratives. Figure 2.13 shows the proportion of associated injury mechanisms that appeared in the narratives. The light shading portion represents mechanisms most likely associated with operation while the darker shading represents those associated with access/ egress or maintenance. Slip and trip appears as the primary mechanism. Issues causing equipment to jerk and bounce, such as hitting potholes or rocks, also appear prominently.

Figure 2.14 shows the classification of mobile equipment related narratives into tasks. The tasks in dark-shading are most commonly associated with the operator of the equipment from the cab or controls. The tasks in mid-shading are associated with access and egress. The tasks in light shading are associated with maintenance.

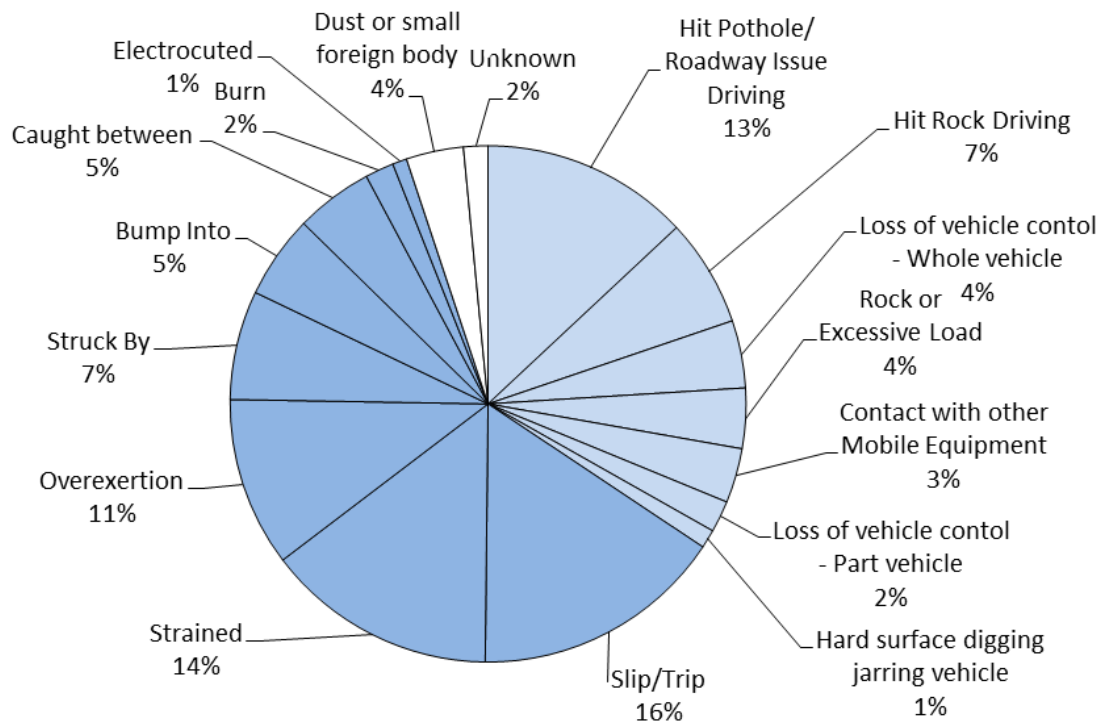


Figure 2.13: Mechanisms of Injury

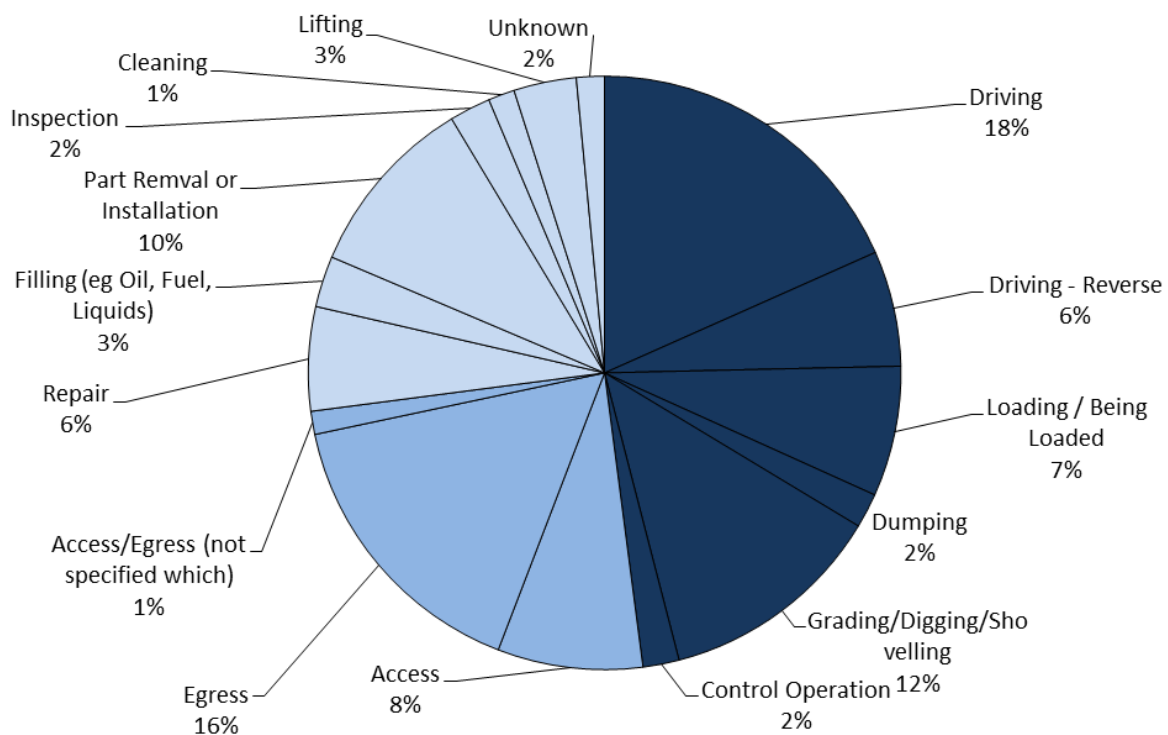


Figure 2.14: Mobile Equipment Narratives By Task

In tasks associated with operations there is a relatively even split with only driving and grading/digging/shovelling standing out in raw numbers. However, these are the general operational tasks associated with different classifications of equipment. Therefore, it may be more specific tasks, such as reversing or loading/being loaded which relatively take up much less operational time, which significantly contributed to the tasks usually within the operational category. In short, no specific area of focus in operations is gained.

Of the tasks almost exclusively associated with maintenance, part removal/install and repair stand out as those worthy of most attention. This is perhaps unsurprising, as they would intuitively be associated with more hazards, especially moving parts and manual handling. This will somewhat assist the analysis but it is suggested that more information is needed to identify specific issues that can be addressed through design. In tasks commonly associated with access/egress, egress is involved in twice as many reported injuries as access. This is consistent with the previous findings of Moore et al (2009). who also found that egress was significantly more prevalent which justifies a particular focus on equipment egress.

2.4.5 Does the location of injury on the body give priority areas to investigate?

Figure 2.15 illustrates the division of injury narratives into specific regions of the body. The darker shading slices are injuries to the lower limbs. The mid-shading slices are injuries to the upper limbs. The lighter shading slices are injuries around the spine. The white represents all other injuries. The only piece of information that is directly taken from the chart is that lower back injuries remain significant in mining. However, injuries to other areas are also common. As noted above, matching these body parts with other variables, like task and/or mechanism, will give a clearer indication of *how* the injuries occurred. However, by itself, information about the part of the body which is injured is not a very useful, indicating that combining the analysis with other variables is needed.

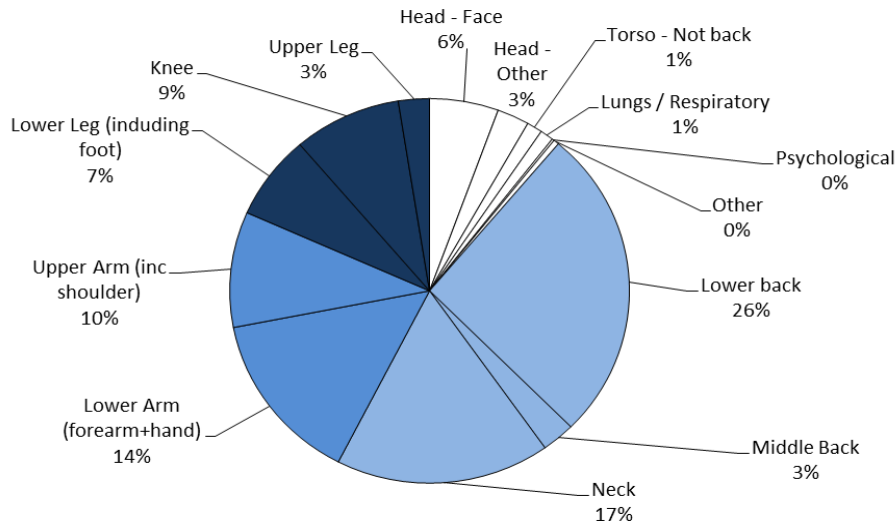


Figure 2.15: Injuries to Body Areas with Colour Linking

2.4.6 Does access/egress remain a priority issue to address?

When looking at the classification of injuries, access and egress was involved 25.2% of the time, compared to 20.1% for maintenance and 54.7% for operational tasks. Access and egress injuries resulted in lost time injuries in 42.1% of cases. The majority of the access and egress injuries (62%) were associated with egress. Whilst tasks in the maintenance and operations category are still of interest, there is remains justification in reviewing access/egress. This is particularly true as the total number, environmental variability and complexity of tasks in operations and maintenance are likely much greater than those with access and egress. Therefore, a focus on improving access and egress still seems a likely path to reducing injury rates associated with surface mobile equipment.

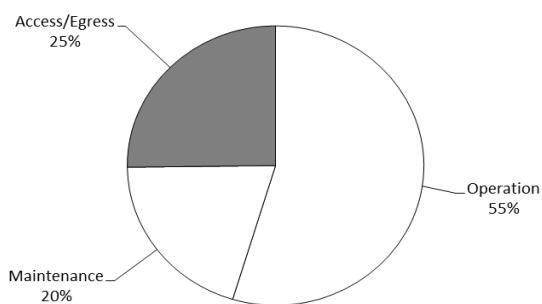


Figure 2.16: Access/Egress, Operations and Maintenance as the Task Category at Injury

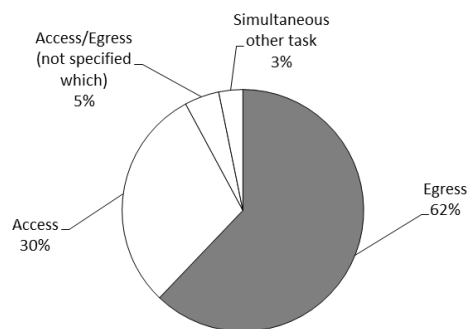


Figure 2.17: Tasks Associated with Access Egress

2.5 Results: Multivariable Inquiry

The following sections describe an investigation of three realistic scenarios using the coded injury narrative data to investigate a particular issue, written from the perspective of three different industry roles.

2.5.1 Safety officer

In this scenario, a safety officer has been tasked with reducing risk related to access and egress of surface mobile mining equipment, especially through equipment design.

Logically, the first step is to constrain tasks by the code 'Access/Egress' within the Activity Category, seen in Table 2.4 (category 3). This leaves 280 injury narratives for investigation. As the safety officer has specifically been tasked with looking at design issues, it is logical that the location of the persons injured would provide some focus.

Table 2.4: Selected code to 'constrain' the search for the safety officer

CATEGORY 3: Activity Category

What Category of task?

Operation

Maintenance

Access/Egress

Therefore, the relationship between the type of equipment (category 1) and the location on equipment (category 2) was explored, as highlighted in red in Table 2.5.

Table 2.5: ‘Access egress’ within the category ‘Activity Category’ was selected to constrain the search (red). Within this constraint ‘type of equipment’ and ‘location on equipment’ were combined (blue).

Equipment	Task	Accident
1 Type of Equipment	3 Activity Category	5 Body Part Injured
2 Location on Equipment	4 Task being Performed	6 Injury Mechanism
		7 Lost Time

Looking at the data visualization of the relationships between the categories of ‘equipment’ and ‘location on equipment’ the safety officer determined that five relationships appeared more prominent than the others and warranted further investigation. The original data visualisation is shown in Figure 2.18 and the relationships warranting priority investigation are shown in Figure 2.19.

The most frequent combination of equipment type and location was of ladders and haul trucks which, with 39 injuries, accounted for 14% of all access and egress related injuries. Ladders associated with bulldozers and excavators were also found to be relationships worthy of investigation. The other relationships between equipment and location within access and egress which were more prominent were light vehicle doorways and the tracks of bulldozers. The safety officer consequently decided to focus on these locations. Table 2.6 show these relationships and the percentage of the total of access and egress related injury narratives.

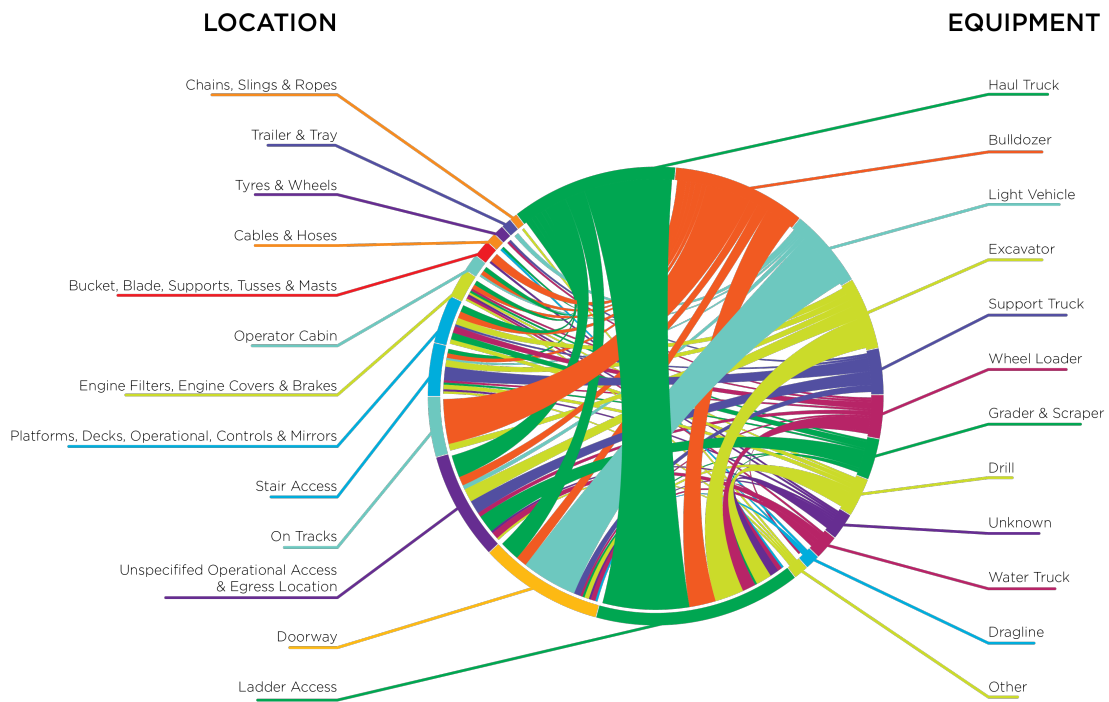


Figure 2.18: Frequency combinations of codes for 'location on equipment' and 'Type of Equipment' within 'access and egress'

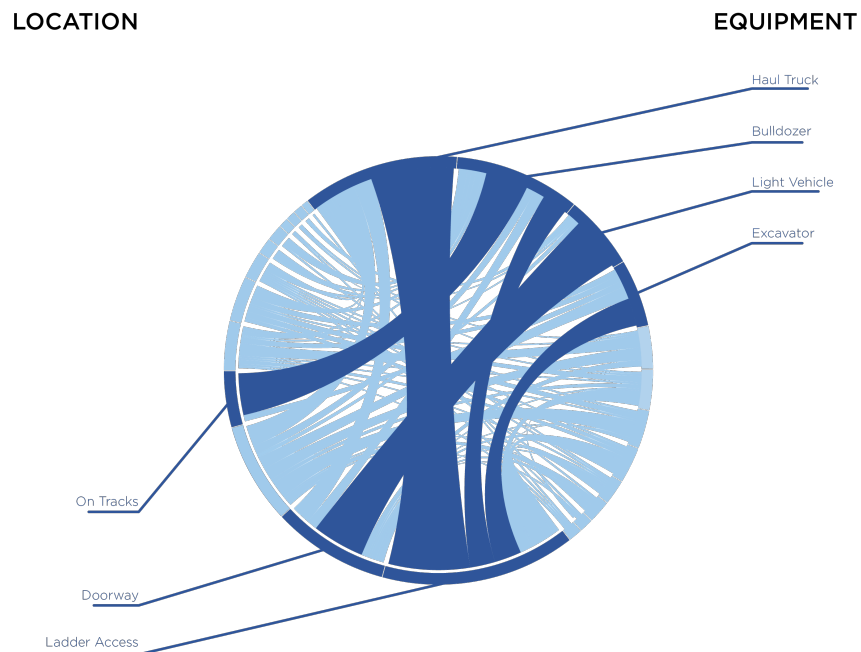


Figure 2.19: Frequency combinations of codes for 'location on equipment' and 'Type of Equipment' within 'access and egress' selected for priority investigation

Table 2.6: Percentages of visually selected frequency combinations of codes for ‘Location on Equipment’ and ‘Type of Equipment’ within ‘access and egress’ selected for priority investigation

Equipment	Location	% of Access Egress Related Injury Narratives
Haul Trucks	Ladders	14%
Light Vehicles	Doorway	9%
Bulldozer	On Tracks	7%
Bulldozer	Ladders	4%
Excavators	Ladders	5%
	TOTAL	39%

Now knowing the physical location targets – *where* the injuries are occurring – the safety officer was also interested in knowing more about *how* the injuries were occurring. To do this, the officer decided to examine the combination of the task being performed and injury mechanism (Table 2.7).

Table 2.7: ‘Operations’ within the category ‘Activity Category’ was selected to constrain the search (red). Within this constraint ‘Task Being Performed’ and ‘Injury Mechanism’ were combined (blue).

Equipment	Task	Accident
1 Type of Equipment	3 Activity Category	5 Body Part Injured
2 Location on Equipment	4 Task being Performed	6 Injury Mechanism
		7 Lost Time

When the relationships are plotted, it is immediately obvious that one is dominant; slipping or tripping during egress which represents 40% of all incidents. There are other relationships that are worthy of note, such as slip/trip during access or strained during egress. All of the relationships can be seen in Figure 2.21 and the selected relationships in Figure 2.22. However, the safety officer concludes that, though these should be considered, prevention of slipping and tripping during egress must be central to any further prevention efforts.

These results cannot tell the safety officer what to change about the design to reduce injuries related to access and egress of mobile equipment, or even if design changes are the best control option. However, it does give focus to begin investigations. The officer decided that the initial focus should be 'non-stair' access/egress points (ladders, tracks etc.) of haul trucks, bulldozers and excavators. When reviewing these physical areas, slipping/tripping and straining during access or egress will be considered. A specific focus will be placed on slipping/tripping during egress.

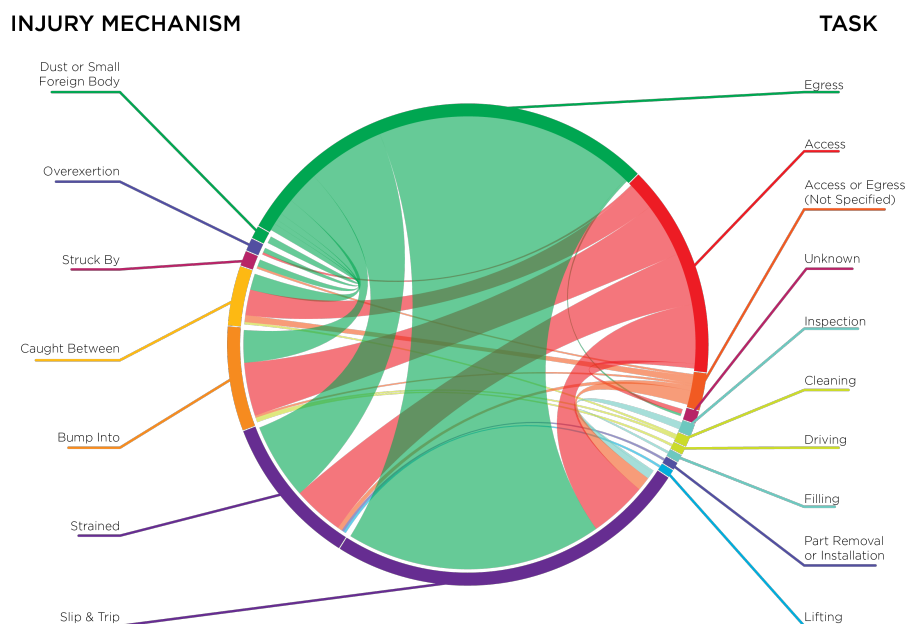


Figure 2.20: Frequency combinations of codes for 'Task being Performed' and 'Injury Mechanism' within 'access and egress' – (Note: Best viewed in colour)

INJURY MECHANISM

TASK

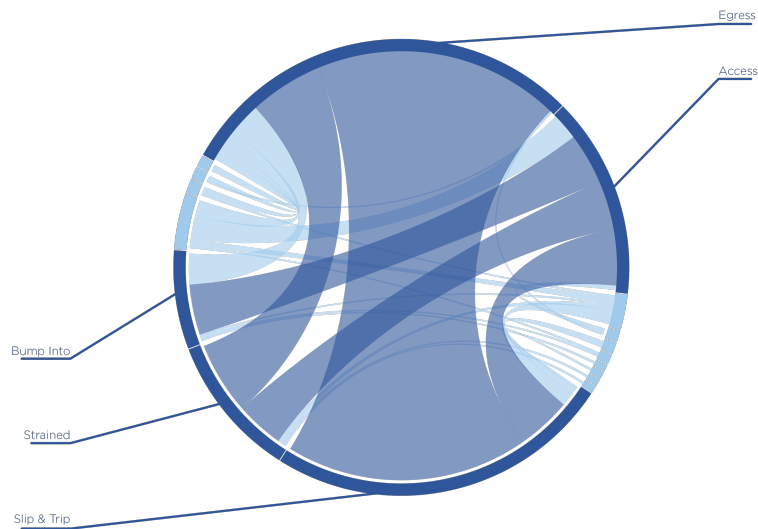


Figure 2.21: Frequency combinations of codes for ‘task being performed’ and ‘injury mechanism’ within ‘access and egress’ selected for priority investigation

Table 2.8: Percentages of visually selected frequency combinations of codes ‘task being performed’ and ‘injury mechanism’ within ‘access and egress’ selected for priority investigation

Task	Mechanism	% of Access Egress Related Injury Narratives
Egress	Slip/Trip	40%
Egress	Strained	12%
Access	Slip/Trip	14%
Access	Strained	8%
Access	Bump into	8%
	TOTAL	81%

2.5.2 Mine Operations Manager

In this example of using the injury narrative analysis classifications as a multi-layered tool, a Mine Operations Manager aims to find some issues to address to reduce injury risk whilst people are operating mobile mining equipment. Therefore, this is a larger scope than the above example which focused on access and egress.

The first step is to constrain tasks by the code 'Operations' within the Activity Category (Table 2.9) to leave only the injury narratives that are relevant to the manager's scope. This leaves 608 injury narratives for investigation. The mine operations manager first wanted to know which equipment in the fleet she should be focusing on reviewing. Therefore, she selected type of equipment (category 6) as one of the codes to combine. She then selected 'body part injured' (category 2) for comparison to see if specific injury types emerged with different equipment. This was to identify which equipment and where her workers are likely to experience an injury.

Looking at the data visualisation, seen in Figures 2.22 and 2.23, the mine operations manager was able to identify four relationships between 'equipment' and 'body part' which warranted further investigation. These were the four between the equipment of haul truck and bulldozers and the body part of the neck and lower back. Table 2.11 shows that when combined these accounted for 46% of injuries related to operations. Therefore, the mine manager decided to initially focus on how haul trucks and bulldozers may cause injuries the spinal column.

Table 2.9: Selected code to 'constrain' the search for the Mine Operations Manager

CATEGORY 3: Activity Category

What Category of task?

Operation

Maintenance

Access/Egress

Table 2.10: ‘Operations’ within the category ‘Activity Category’ was selected to constrain the search (red). Within this constraint ‘Type of Equipment’ and ‘Body Part Injured’ were combined (blue).

Equipment	Task	Accident
1 Type of Equipment	3 Activity Category	5 Body Part Injured
2 Location on Equipment	4 Task being Performed	6 Injury Mechanism
		7 Lost Time

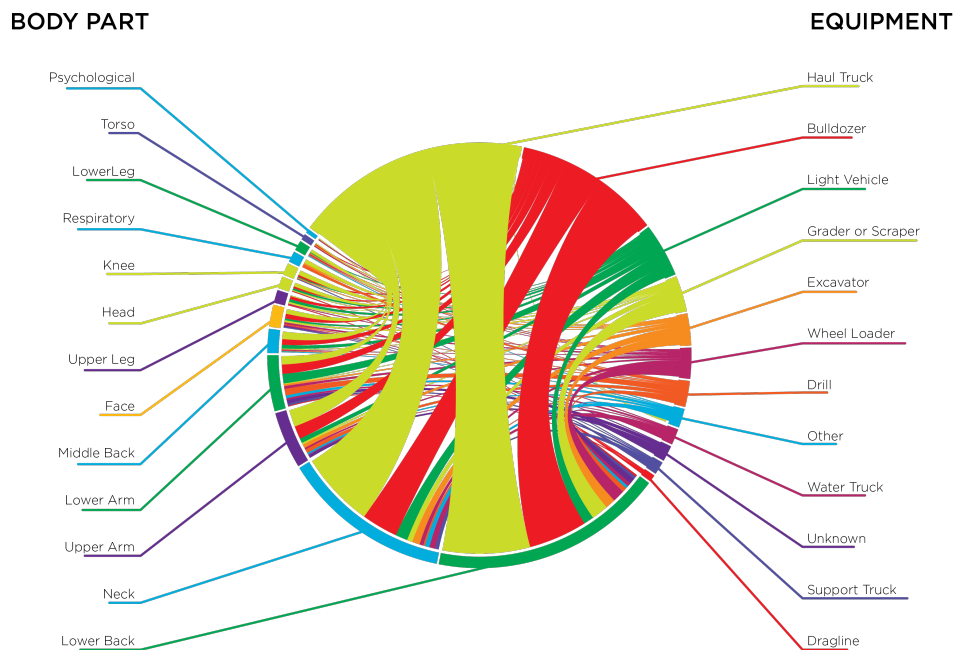


Figure 2.22: Frequency combinations of codes for ‘Body Part Injured’ and ‘Type of Equipment’ within ‘Operations’

BODY PART

EQUIPMENT

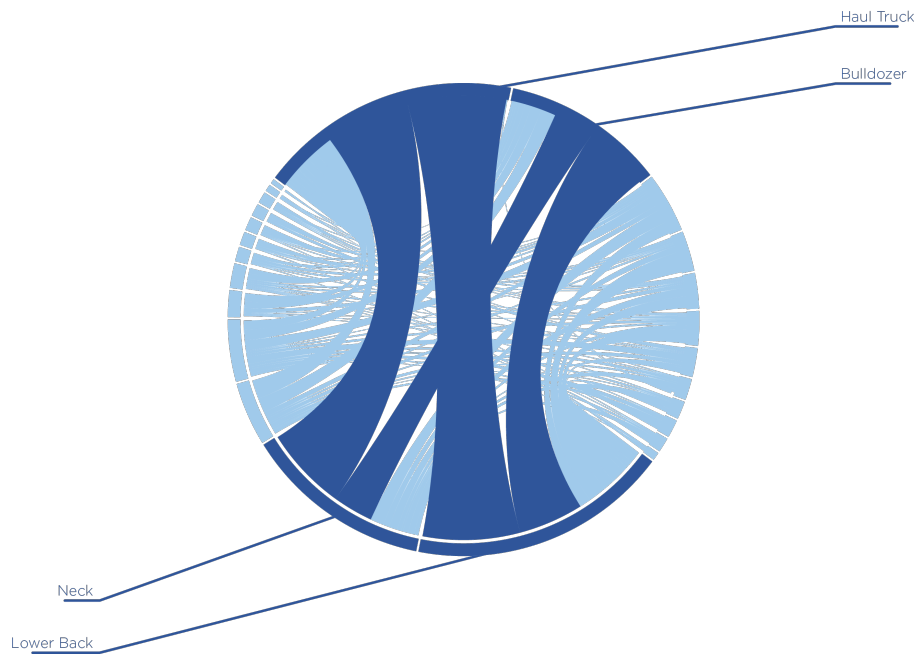


Figure 2.23: Frequency combinations of codes for 'Body Part Injured' and 'Type of Equipment' within 'Operations'

Table 2.1: Percentages of visually selected frequency combinations of codes 'Type of Equipment' and 'Mechanism of Injury' within 'operations' selected for priority investigation

Equipment Involved	Body Part Injured	% of Total Injuries Associated with Operations
Haul Truck	Lower Back	15%
Haul Truck	Neck	13%
Bulldozer	Lower Back	10%
Bulldozer	Neck	6%
	TOTAL	46%

However, investigating operational injuries to the spinal column occurring with bulldozers/haul trucks is still quite a large focus. Investigating further, the Mine Operations Manager combined the constrained injury narratives categories of task being performed (category 4) and injury mechanism (category 6).

Table 2.12: Operations’ within the category ‘Activity Category’ was selected to constrain the search (red). Within this constraint ‘Task Being Performed and ‘Injury Mechanism’ were combined (blue).

Equipment	Task	Accident
1 Type of Equipment	3 Activity Category	5 Body Part Injured
2 Location on Equipment	4 Task being Performed	6 Injury Mechanism
		7 Lost Time

Six relationships, seen in Figures 2.24 and 2.45, emerged as being larger than others and therefore a priority for investigation. Two of these related to trucks being loaded with the injuries being caused by either contact between truck and shovel or the shovel overloading the truck. There also appeared to be mechanisms during driving and movement of soil/ore that could have been related to overuse, such as vibration, or unexpected jerky movement. All of these are consistent with the above finding that the spinal column is the most prominently injured body area. This suggests that the Mine Operations Manager should begin further analysis with driving, loading/being loaded, as it is an easily constrained environment. Sources of vibration and jerking will also be reviewed such as potholes and equipment maintenance, and design changes to reduce the effect of these sources on the driver, such as improve suspension and seating will be assessed.

INJURY MECHANISM

TASK

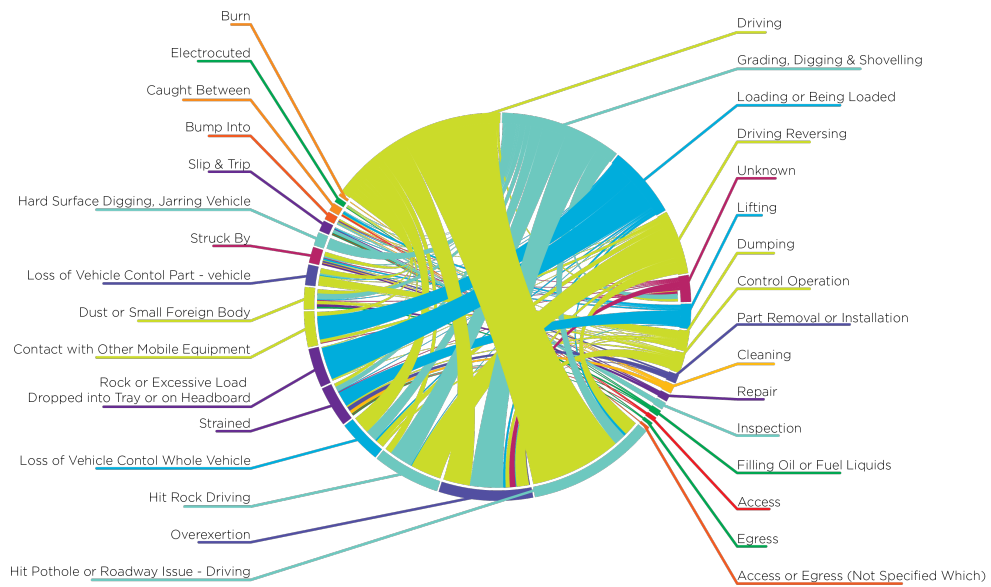


Figure 2.24: Frequency combinations of codes for 'Injury Mechanism' and 'Task Being Performed' within 'Operations'

INJURY MECHANISM

TASK

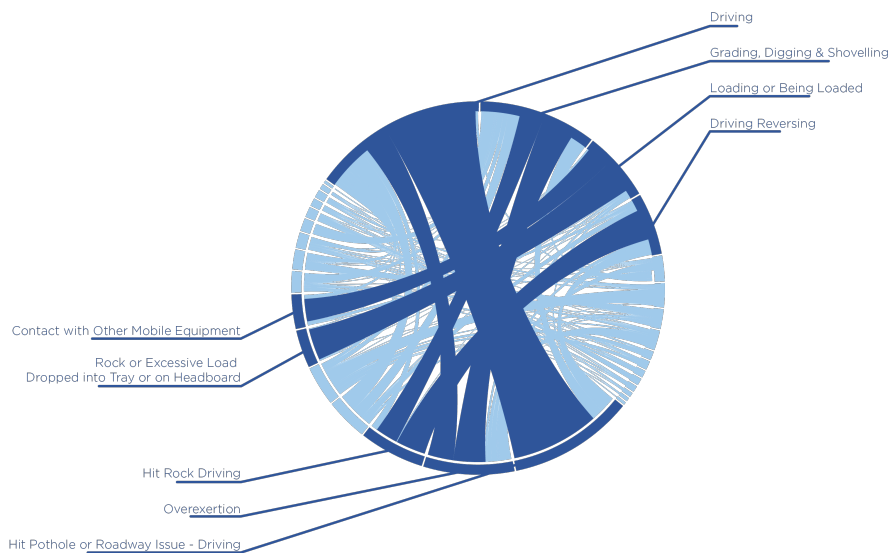


Figure 2.25: Frequency combinations of codes for 'Injury Mechanism' and 'Task Being Performed' within 'Operation' selected for priority investigation

Table 2.13: Percentages of visually selected frequency combinations of codes ‘Injury Mechanism’ and ‘Task Being Performed’ within ‘Operations’ selected for priority investigation

Task	Mechanism	% of Total Associated with Operations
Driving	Hit Pothole/ Roadway Issue Driving	18%
Grading/Digging/Shovelling	Overexertion	7%
Loading/Being Loaded	Rock Or Excessive Load Dropped Into Tray Or On Headboard	7%
Driving Reverse	Hit Rock Driving	6%
Driving	Overexertion	5%
Grading/Digging/Shovelling	Hit Rock Driving	5%
Loading/Being Loaded	Contact With Other Mobile Equipment	5%
	TOTAL	52%

2.5.3 Bulldozer Equipment Designer

In this example of using the coded injury narrative analysis, a person leading a team designing a new bulldozer model was interested in determining areas of focus for improved safety in design. The first step is to include only the injury narratives with bulldozers in the ‘type of equipment’ category, as shown in Table 2.14. In designing mobile equipment, individual persons or small teams are primarily responsible for subsections of the equipment. Therefore, the lead designer determined that *location on equipment* and *task being performed* would give an indication of the human machine interaction points that are worthy of further attention in each specialist area.

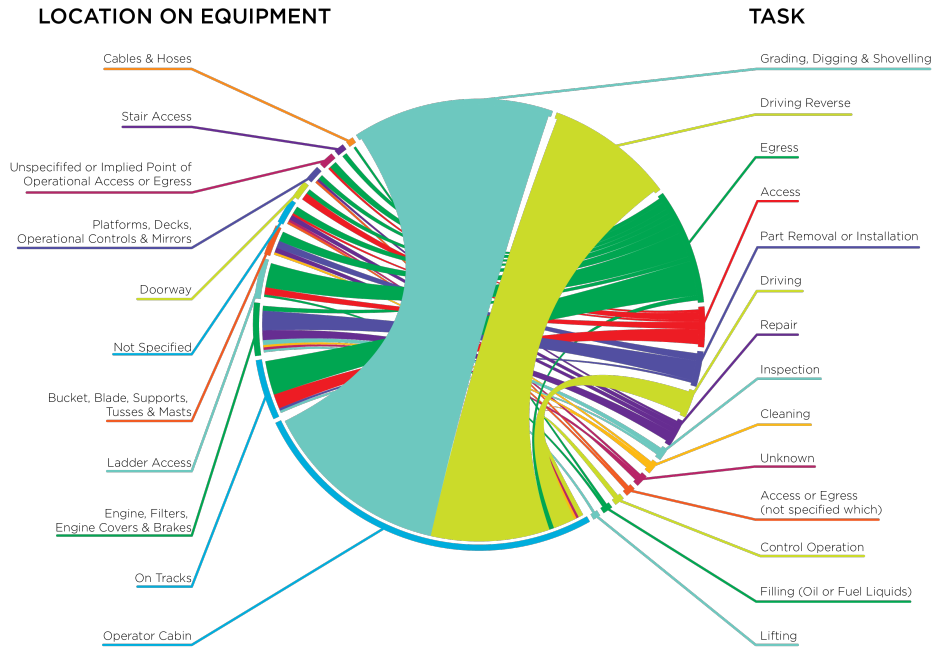
From the visualisation, see in Figures 2.26 and 2.27, five relationships accounting for 73% of incidents were identified for further investigation. Three of these related to the general operational tasks in the operator cabin, two to egress and one to installation or removal of engine parts. These three distinct sets of problems were provided to the teams designing each area of the equipment for consideration.

Table 2.14: Selected code to ‘constrain’ the search for the Bulldozer Equipment Designer

1: Type of Equipment	
<i>What type of equipment was involved?</i>	
Haul Truck	Bulldozer
Grader/Scraper	Water Truck
Light Vehicles (Troup Carriers, Utes, etc)	Wheel Loader
Truck (not haul – smaller)	Dragline
Drill	Excavator
Other	Unknown

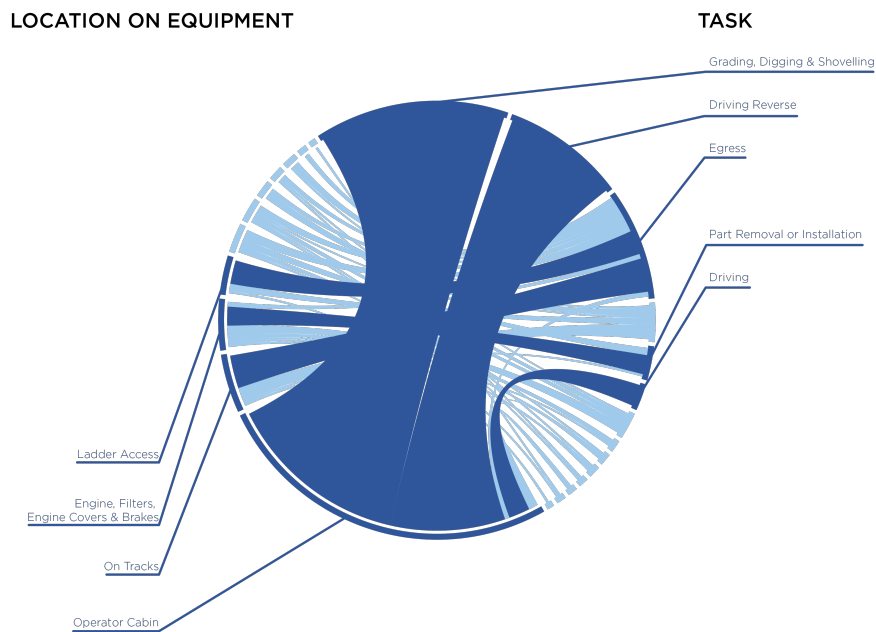
Table 2.15: ‘Bulldozer’ within the category ‘Type of Equipment’ was selected to constrain the search (red). Within this constraint ‘Location on Equipment’ and ‘Task being Performed’ were combined (blue).

Equipment	Task	Accident
1 Type of Equipment	3 Activity Category	5 Body Part Injured
2 Location on Equipment	4 Task being Performed	6 Injury Mechanism
		7 Lost Time



3.1

Figure 2.26: Frequency combinations of codes for 'Location on Equipment and 'Task Being Performed' within 'Bulldozer'



3.1

Figure 2.27: Frequency combinations of codes for Location on Equipment and 'Task Being Performed' within 'Bulldozer' selected for priority investigation

Table 2.16: Percentages of visually selected frequency combinations of codes Location on Equipment and ‘Task Being Performed’ within ‘Bulldozer’ selected for priority investigation

Location	Task	% of Total Associated with Bulldozers
Operator Cabin	Grading/Digging/Shovelling	34%
Operator Cabin	Driving Reverse	21%
Operator Cabin	Driving	4%
On Tracks	Egress	6%
Ladder Access	Egress	4%
Engine/Filters/ Engine Covers/Brakes	Part Removal or Installation	3%
	TOTAL	73%

Whilst this information gave the teams some distinct information that was relevant to their area, it did not explain how task performance in a specific location lead to an injury. The designers have an indication of where to look, but not what they should be looking for in these areas. Fortunately, the three categories of location, as set out above, neatly divide into the three activity categories: operations, maintenance and access/egress. Consequently, the lead designer decided to use *activity category* combined with *injury mechanism*. This would give an indication to each of the teams designing the parts of the equipment of the specific hazards that should be given particular attention.

When this combination was examined, four mechanisms emerged from the visualisations shown in figures 2.28 and 2.29. Two of these, overexertion and hit pothole, are likely to be related to acute jolts and long term exposure to whole body vibration. The others, hit rock while driving and loss of whole vehicle control, point to specific causes such as visibility and stability. As would be expected, the access/egress designers are pointed towards slipping and tripping being the major issue. However, straining was also noted in a large number of cases indicating that some manual tasks assessment, to review the forces and postures required, would be

valid. Overall, the combination of variables was able to provide specific issues to the designers responsible to address in relation to different parts of the equipment.

Table 2.17: ‘Bulldozer’ within the category ‘Type of Equipment’ was selected to constrain the search (red). Within this constraint ‘Activity Category’ and ‘Injury Mechanism’ were combined (blue).

Equipment	Task	Accident
1 Type of Equipment	3 Activity Category	5 Body Part Injured
2 Location on Equipment	4 Task being Performed	6 Injury Mechanism
		7 Lost Time

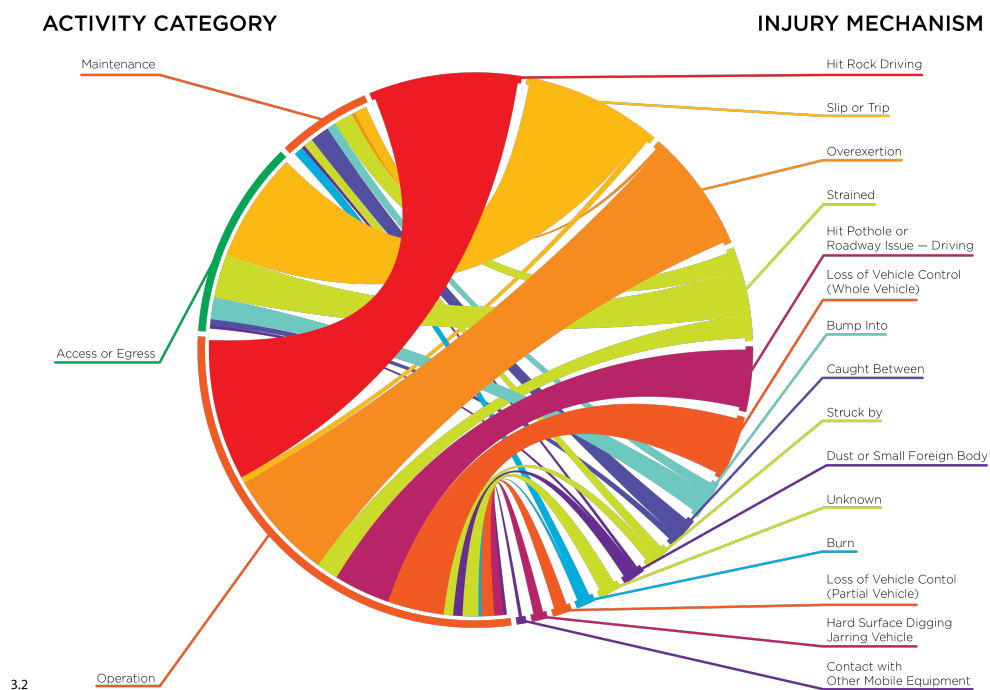


Figure 2.28: Frequency combinations of codes for ‘Activity Category’ and ‘Injury Mechanism’ within ‘Bulldozer’

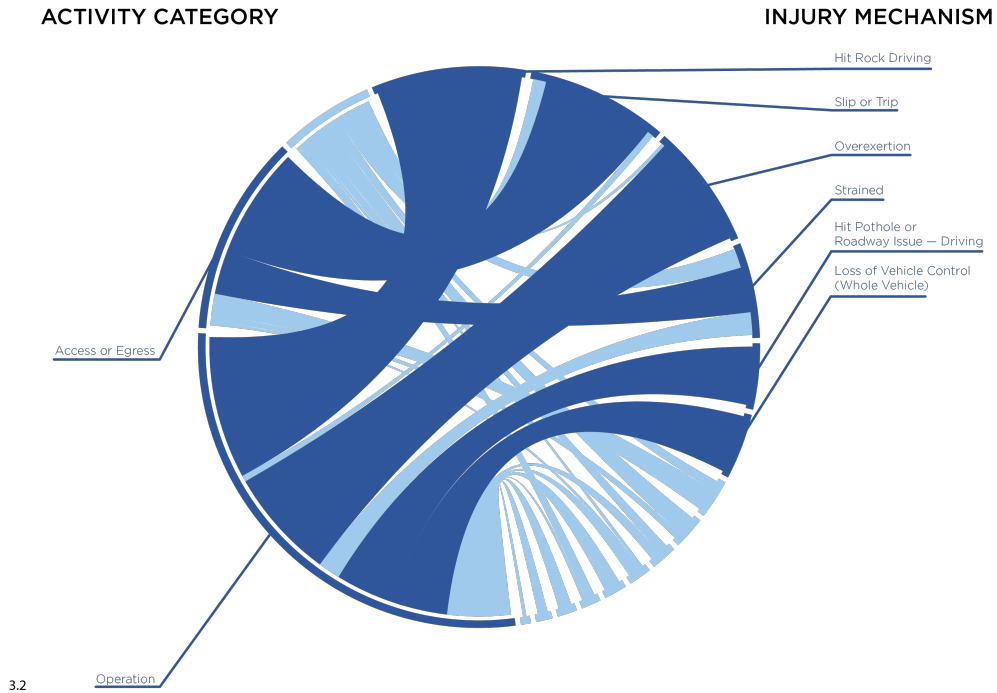


Figure 2.29: Frequency combinations of codes for Activity Category’ and ‘Injury Mechanism’ within ‘Bulldozer’ selected for priority investigation.

Table 2.18: Percentages of visually selected frequency combinations of codes ‘Activity Category’ and ‘Injury Mechanism’ within ‘Bulldozer’ selected for priority investigation

Activity Category	Injury Mechanism	% of Total Associated with Bulldozers
Operation	Hit Rock	21%
Operation	Overexertion	15%
Operation	Hit Pothole / Roadway Issue	8%
Operation	Loss of vehicle control (Whole vehicle)	8%
Access/Egress	Slip Trip	15%
Access/Egress	Strained	6%
TOTAL		73%

2.5.4 Summary of multivariable findings

Issues that the above three examples were trying to address could have been approached by looking at variables individually, as was done in the previous section. However, this would have resulted in the commencing an on-site investigation with too broad a focus. It is difficult to obtain the appropriate resources to apply human factors tools in mining environments. Without a more targeted approach, it is likely that further investigation would be compromised, and considered particularly time-consuming in relation to benefit. By combining the variables into a hazard pattern which is relevant to a specific scope, all of the case studies included evidence-based specific focus areas at the commencement of the investigation. In summary, creating hazard patterns, using multiple layers of variables, is a useful way to commence the application of human factors methods in mining.

2.6 Discussion

2.6.1 Main findings

There were three main findings. Firstly, it was demonstrated that detailed consideration of narratives describing injuries associated with surface mining equipment allows user-centred issues, such as task, specific location and mechanism, to be identified. This finding is comparable to results of similar analysis of underground coal mining injuries (Burgess-Limerick, 2011).

Secondly, there was sometimes sufficient specificity in the extracted coding to allow some key issues to emerge when only looking at a single variable (eg. equipment access). However, it is more common that a single category could only show broad trends.

Thirdly, it was shown that by simultaneously considering multiple layers of the task-related information, more specific issues emerged for closer examination. This layering can be done graphically, allowing issues to be identified visually. This mode of data analysis could lead to design changes that will efficiently and effectively reduce the risk of injury when interacting with surface mobile mining equipment, at least from sources that have been significant in the past. The categories noted

above could serve as a model for future injury narrative analysis of surface mining equipment.

2.6.2 Inferred Global Use

For this study the use of inferential statistics was not appropriate because the data consistent of the whole population of injuries occurring at NSW surface coal mines within a 5 year interval. It cannot be treated as a random sample of worldwide mining industries. However, human factors practitioners have identified that mining in advanced economies has significant commonalities in equipment, mining methods and workforce skills (Horberry & Cooke, 2012). Although there are some differences in legislation and culture, in the absence of other measures it can be inferred that the injury pattern is likely to be similar in other surface coal mines and, in fact, surface mines in general. Therefore, the findings can be used as a cautious estimate of global issues, and the methods developed could certainly apply to different incident populations.

2.6.3 Accuracy and Specificity of Data Extracted from Injury Narratives

It was noted in the introduction that methods involving injury narratives have heavily rely on the accuracy and content of the data which is recorded by multiple third parties. In regards to accuracy, it is unknown how much error may occur in reporting, though with non-causative issues it is logically likely that the information that *is* included is accurate enough for the aim of identifying key trends.

However, a greater problem exists with the information that *is not* present. In a minority, but significant, number of cases the narrative did not contain enough information to provide a code. For example, location on equipment during access and egress was unknown for 15% of cases. However, perhaps more importantly, many codes were required to be quite general. For example the category of 'strained' in injury mechanism and 'engine/filters/engine covers/brakes' needed to be broad otherwise a significant amount of data would have remained un-coded.

Alternatively, the use of very specific categories can give low rates of coding making the data practically unusable. For example, Williamson et al found this was a problem when coding narratives investigation of industrial fatalities across three

countries with the successful coding in some categories as low as 16% (Williamson, Feyer et al., 2001). This limits the granularity of further investigation, and may bias towards issues that were more easily identified.

2.6.4 Recommendations for future work

2.6.4.1 Improve Method of Collecting and Coding Injury Narratives

In future work it is recommended that the method for recording injury narratives be revisited, in order to maximise accuracy and usefulness. It is unlikely, in a practical sense, that the skill and knowledge of those collecting data can be improved.

Therefore, addressing the method of data collection seems the most expedient route to this goal. Bondy et al (2005) suggest:

“Forms guiding investigators to explicitly consider human, organizational, and environmental factors could foster more complete descriptions of factors contributing to... injury” (Bondy, Lipscomb et al., 2005).

In these data, the injury narrative is derived from the answer to the question: “describe how the incident occurred” with space for 1 to 2 sentences. Revisiting this instruction is recommended, with trials to see what instructions or method gain the richest and most accurate information. Traditionally, this revisiting has seen a reductionist method where multiple questions are asked and the reporter can pick from a pre-existing list of codes. However, this limits the flexibility and richness of the information to only the codes that were predicted to be useful. Therefore, it is specifically recommended that lengthening the instruction to the narrative be considered. The altered instructions would include reference to the minimum information required in an injury narrative, such as equipment type and injury mechanism, without discouraging the reporter from including other information.

2.6.4.2 Develop the Multivariate Method and Test Use

The multivariate method was demonstrated to be an effective data exploration approach to identify issues for detailed examination. It is recommended that this method be trialled from more perspectives than merely those specified here such as regulators, training managers and maintenance managers. However, the workload

to construct the multi-variable graphs, and lag time in data classification, is currently a significant barrier to widespread and effective use of the technique in industrial settings.

To overcome this problem, it is recommended that interactive software be developed to construct the graphs and perform the analysis. This may include re-thinking the visualisation format, such as altering the output to be in rows rather than in a circle as seen in Figure 2.31. It is also recommended that coding of narratives be undertaken as they are submitted with a database across multiple jurisdictions. It may be possible, over time, to automate some of the coding through keyword matching. Previous efforts in this have indicated some success, though manual coding is still needed in a significant number of cases (Lincoln, Sorock et al., 2004). Regardless of how the data are coded, a database would transform a one-time narrative analysis classification into a human factors tool that could be interrogated from a variety of perspectives using up-to-date information. Observing how this tool was used by industry professionals, and any resultant decisions, could then form a future path of research. This could, ultimately, include longitudinal studies detailing the effectiveness of using this method to target strategies.

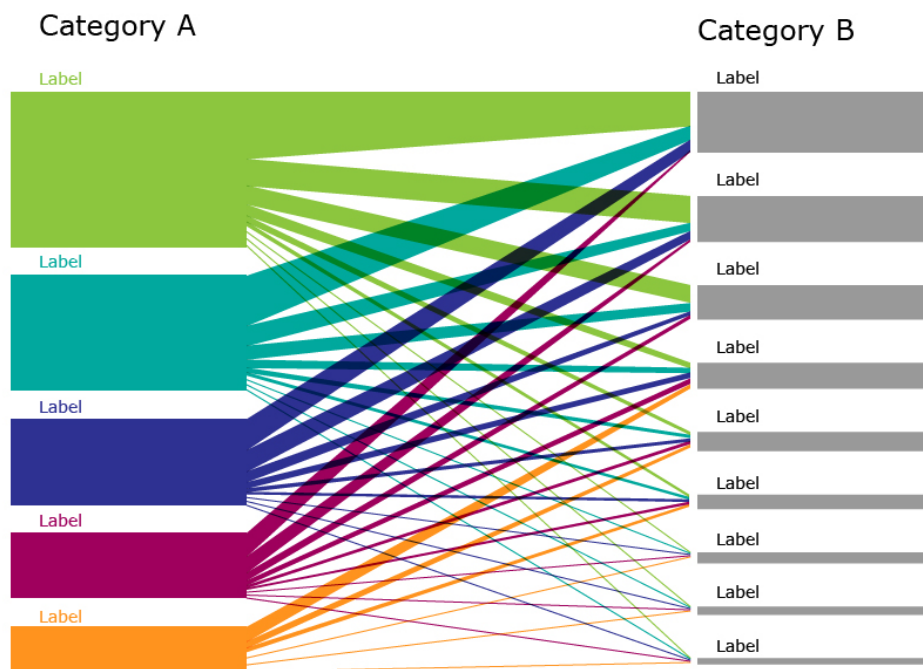


Figure 2.30: Possible change of visualisation in 'row' rather than circle format

2.6.5 Conclusion

Mobile equipment was associated with the majority of surface coal mining injuries and the largest proportion of injuries happened during operation and access/egress. The utility of a multivariate graphical analysis technique was demonstrated through three scenarios. The technique was demonstrated to allow identification of operator-centred issues and can therefore be considered a useful human factors technique. The resulting increase in specificity for further investigation can lead to improved effectiveness of interventions. A number of the issues identified (eg vehicle collisions and warning systems) are targeted in later chapters of this thesis.

Chapter 3

Cognitive Task Analysis for Incident Investigation with Mobile Mining Equipment Operators

Abstract

The analysis of injury narratives in Chapter 2 revealed that incidents involving operation of mobile mining equipment were prevalent. Little is known about the decision making strategies of operators which might contribute to these incidents. The Critical Decision Method (CDM), from the broader discipline of Cognitive Task Analysis (CTA), uses specific interviewing techniques to understand in detail how key decisions are made in complex or fast-paced environments. The Decision Ladder is a decision model used in Cognitive Work Analysis (CWA) to directly support design decisions. These techniques were used to attempt to understand the cognitive demands of operating mobile mining equipment.

Data were collected from nine experienced mining equipment operators on two visits to surface coal mines. The subject matter was an incident where the operator was a central decision maker. The CDM was deployed on-site and later interpreted using the Decision Ladder. Results were compared to existing incident investigations where they could be obtained. This could then be translated into Decision Ladders and specific design suggestions.

Overall, all of the trials were able to provide a rich, operator-centred narrative. Extra information, and subsequent recommendations, was revealed in all of six incidents where an investigation report was available. Jumps on the Decision Ladder appeared naturalistic, giving some indication that explicit and simultaneous consideration of multiple options is probably uncommon for equipment operators. Overall this is a much deeper description of the incident event than the standard investigation techniques used in much of the minerals industry today. It is recommended that further work be done to standardise the combination of the methods into a toolkit and this be more widely investigated in mining incident

investigation processes. Applying the method proactively is an attractive topic for future research.

3.1 Introduction

The review of injury narratives in Chapter two identified that a significant number of injuries occur while surface mobile mining equipment is in operation. Frequent injuries were related to loading, driving, grading and shovelling. Serious injuries and deaths have also occurred related to issues such as collision, rollover and other losses of control (Kecojevic & Radomsky, 2004; Kecojevic, Komlijenovic et al., 2007). There have been some industry attempts to reduce these issues, such as the introduction of physical risk controls, such as rollover protection in cabs, and technological solutions such as proximity detection systems. Without an appropriate understanding of the tasks involved, the introduction of risk controls requires significant assumptions. This is especially so for those which hope to avoid an initiating event from an operator error. The absence of investigation could lead to the introduction of ineffective, even harmful, controls.

Mobile mining equipment operation is largely a cognitive task, with safety depending on operators continually scanning the environment and making decisions to avoid hazards (Horberry, Burgess-Limerick et al, 2010). Any tools that will aid design should reveal this cognitive work in a way that is usable. It is quite similar to the cognition involved with on-road driving, which has previously been described as principally a cognitive activity where the drivers are searching for disturbances that could signal an emerging hazard even whenever the system is stable (Klein, Pliske et al., 2005). CTA aims to reveal these non-observable, mental components of work tasks including how information is gained from the environment (Roth, 2008).

In this chapter, the aim was to attempt to use CTA to elicit and represent the experiences of mobile mining equipment users in a way that could be used to influence design. The knowledge *elicitation* was performed using methods adapted from CTA, because these techniques are regarded as being the best developed to understand real-world (naturalistic) decision making. The CDM was selected for use. Methods from Cognitive Work Analysis were adapted for knowledge *representation*

because these methods are well regarded in their use in system design. The Decision Ladder was selected for use.

3.1.1 Relationship to the Asset Lifecycle

CDM has generally been applied to the investigation of actual incidents with existing equipment. Therefore, its primary use in the Asset Lifecycle is at the operation and training stage, with the potential to lead to modifications or retrofits. However, the use of information gained from CDM has been commonly used to help design training programs intended to help novice decision makers become experts rather than design changes. The Decision Ladder is used to make a clearer link to how the design of mobile mining equipment might be modified to facilitate improved decision making. This may be through, for example, greater relevance of audible and visual information given by in-cab displays to haul truck operators or how to better reveal the information which maintainers can use to diagnose equipment faults.

There is also the potential to use CDM within concept and prototyping stages of design. Designers may use the CDM process to engage experts in a forwards-looking CDM in a conjured situation to anticipate how design changes might affect their decisions. It could also be used in conjunction with actual human performance on a prototype or simulator to predict how decisions will be made in the field. O'Hare et al have done work in this area in a variety of fields including decision making for pilots and emergency ambulance dispatchers (O'Hare, Wiggins et al., 1998). Similarly, to the above noted application, the Decision Ladder can be used to help understand how decisions are likely to be made. These two applications are shown in Figure 3.1.

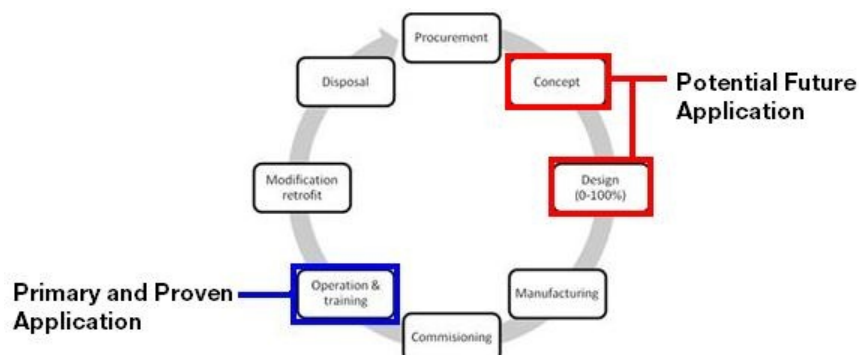


Figure 3.1: CDM & the Decision Ladder can be applied now and in the future

3.1.2 Cognitive Task Analysis for Incident Investigation

3.1.2.1 Naturalistic Decision Making

CTA is heavily reliant on the paradigm of *Naturalistic Decision Making* (NDM) which is the study, and theories, of how people make decisions in real world settings (Klein, 1997). It has its beginnings in the rejection of Subjective Expected Utility theory where people are thought to make decisions by analysing all possible outcomes of a situation in a very rationalistic manner and selecting the most desirable option (Gore, Banks et al., 2006). Early researchers in NDM, including Gary Klein, found that in real situations people generated a very limited number of possible courses of action, sometimes only one, and then compared them to the constraints of the situation for a reason to reject the course of action (Klein, 2008). The first course of action not rejected is taken. People often use mental shortcuts or 'rules of thumb' or heuristics to make these decisions. Experts have developed heuristics with experience that are usually efficient and effective (Dew, Read et al., 2009). This makes experts more sensitive to environmental cues for problem detection as they attempt to understand and sense the environment (Klein, Pliske et al, 2005). More shortcuts are taken when there is less time available. This theory of decision making is summarised in the Recognition Primed Decision (RPD) model (Klein, 2008) shown in Figure 3.2.

3.1.2.2 Knowledge Elicitation in Complex Sociotechnical Systems

Mining can be described as a *Complex Sociotechnical System*. Decisions in Complex Sociotechnical Systems are often made using *tacit* or *inert* knowledge: knowledge that persons have but have not previously, explicitly, considered or expressed (Hoffman, 2008). Therefore, simply asking persons what they were thinking at the time of an incident is unlikely to be enough. For example, classic studies from Nisbett and Wilson (2005) and Bainbridge (1999) found that people can learn to control and make decisions in complex situations without being able to easily verbalise their thoughts and actions. Consequently, in complex situations, knowledge has to be specifically *elicited* from the persons involved. This is commonly called Knowledge Elicitation. CTA methods attempt to provide scaffolding for Knowledge Elicitation. The underlying goal, and assumption, of CTA is that an increased understanding of how people actually make decisions within various complex domains through eliciting tacit knowledge will allow future improvement of these

decisions either through training or changes to environment, including equipment design.

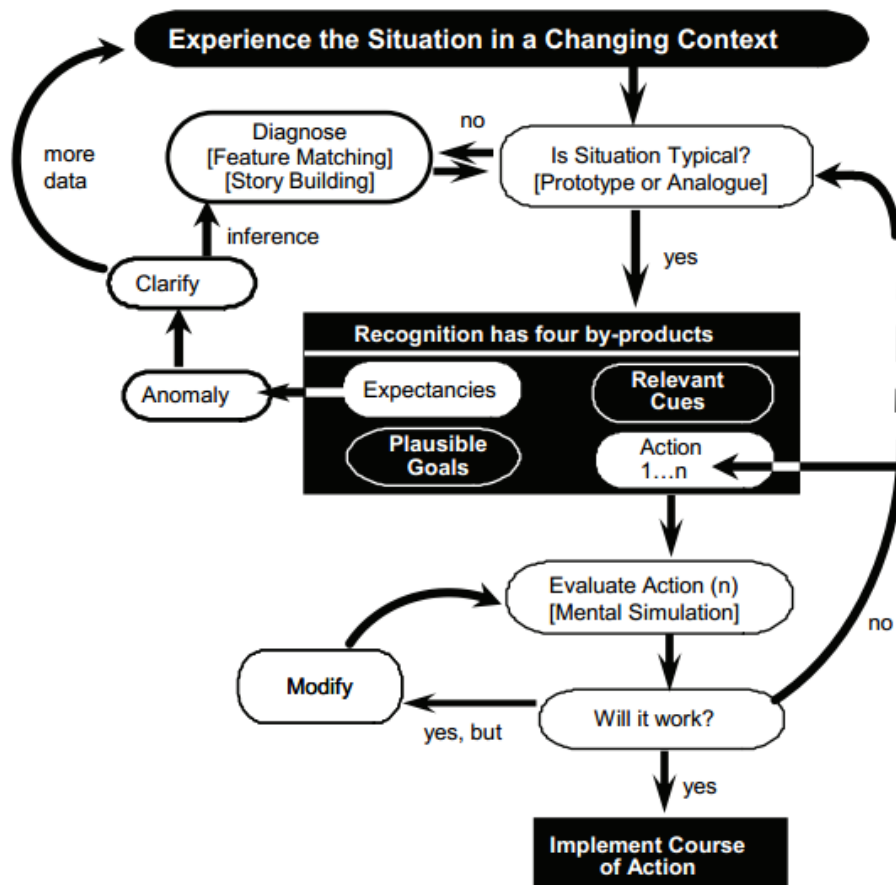


Figure 3.2: A model of naturalistic decision making (from Naikar, 2010)

3.1.2.3 Incident Investigation using Cognitive Task Analysis

Traditional incident identification techniques deal mainly with the identification of a sequence of events, hoping to identify unsafe acts or conditions: *what* happened (Doytchev & Szvilus, 2009). Some go beyond looking at causal analysis to identify the relationship between incident events and the breakdown of any controls: *how* it happened (Simpson, Horberry et al., 2009). However, it has been suggested that new techniques are required to better understand what factors influence and predispose the decisions of mining equipment operators (Horberry, Burgess-Limerick et al., 2010). It is suggested that alternative investigation techniques are needed to help understand the incident, and decisions, from the perspective of the person making those decisions to give an appropriate representation of why the incident

occurred. They would be particularly useful in real world situations where people made critical decisions that significantly contributed to the occurrence or prevention of an incident.

CTA techniques go further than the knowledge elicitation noted above, and also analyse and represent decision making in real world contexts (Crandall, Klein et al., 2006). It is particularly useful in situations where people made critical decisions that significantly contributed to the occurrence or prevention of an incident. CTA assumes that persons were attempting to make sense of the information at hand (Crandall, Klein et al., 2006). Therefore, the investigation aims to understand the incident, and decisions, from the perspective of the person making those decisions: *why* it happened. CTA methods have been described as having four stages; identifying expertise, elicitation of knowledge, codifying it representing knowledge and, finally, application of that knowledge (Klein, 1996; Crandall, Klein et al., 2006). This application can then be used to alter environmental cues to improve decision making.

3.1.2.4 Cognitive Task Analysis in Mining

CTA appears very suited to understanding incidents related to mobile mining equipment where the decisions of experienced operators and maintainers in a complex environment are often related to causing, or preventing, accidents. However, a review of the literature indicates that no systematic investigation of CTA has been undertaken in mining equipment operation. Perhaps the closest study in the minerals industry of CTA application was performed by Dal Santo (2005). This work investigated ground control decisions made by mining engineers working in underground mines to prevent rock falls. There were two main findings. Firstly, the ability of mining engineers to be able to 'read the ground' and make assessments with visual inspections was extremely important. Secondly, the characteristics of decision making changed not only with experience, but also with motivation, expectation and specific hazard knowledge. The key focus of Dal Santo's work was improving the design of ground control education and training, where it appeared that CTA and related approaches could be of considerable benefit. It also indicated that the method could potentially be applied to other issues in mining where people

are actively making operational decisions. It appears valid to trial CTA based methods to reduce injuries related to decision making.

3.1.3 The Critical Decision Method

3.1.3.1 Background

There are a variety of knowledge elicitation methods within CTA which vary in maturity, efficiency and effectiveness (Hoffman, 2008). The Critical Decision Method (CDM) is perhaps the most mature and has been found to be effective in revealing expert knowledge, especially tacit knowledge, reasoning, sense-making and decision strategies (Crandall, Klein and Hoffman, 2006). CDM is a structured interview process that can be used to elicit information and knowledge from experienced operators about their decision-making, understanding and problem-solving processes during non-routine critical incidents (Crandall, Klein et al., 2006).

Critical incidents are targeted as they are believed to reveal more about decision making that occurs within complex sociotechnical systems than routine events. This is because they have potential to show how the systems fail, or could fail, and how experts respond to prevent this from occurring. Additionally, as CDM relies on memory, it has been argued that experts mostly have clear memories of salient or unusual safety-related incidents (Crandall, Klein et al., 2006). The method involves the use of 'probe' questions to uncover the kinds of knowledge on which critical decisions are based. The technique allows interviews to shift interviewees thinking from operational and general accounts of an incident into a more descriptive re-telling of their problem solving processes during the critical incident. In its current format, it has been applied and documented in various domains including, intensive care nursing, fire fighting and the United States military (Roth, 2008).

3.1.3.2 History of the Method

The CDM builds on the earlier Critical Incident Technique that was first developed during World War II and applied to a variety of situations through the study of near misses in the US Airforce (Flanagan, 1954). The Critical Incident Technique is flexible, and represents a more generalised approach to investigating incidents rather than a specific tool (Chell, 2004). CDM is based on this approach, but is a more structured and detailed method. Previous work has examined CDM in other

fields such as nuclear power, aviation, healthcare (Gore, Banks et al., 2006) and intelligence analysis (Hutchins, Pirolli et al., 2004). It was used primarily to identify perceptual and cognitive needs for aiding decision making, and to investigate incidents by reconstructing and understanding how operators made sense of the emergent situations (Klein, 2008). In one particularly relevant example, Tichon (2007) successfully used CDM to elicit knowledge from train drivers, identifying environmental cues, actions to be taken and possible errors.

3.1.3.3 Description of the Method

CDM is a semi-structured interview process usually undertaken by two researchers; one primarily an interviewer and one primarily a note-taker. The participant is preferably an expert in the work domain, though interviews with people of various degrees of experience can be undertaken. The time required varies considerably, being longest in fields with significant expertise in judging extremely complex systems, such as weather forecasting (Hoffman, Coffey et al., 2002). However, in most fields, interviews have been noted to take approximately two hours per participant with significantly more time for the preparation and post-interview analysis. This makes CDM convenient for use in mining as it is usually possible to obtain experts for this length of time at mine sites. Obtaining them for longer periods of time or offsite is very difficult, which would be necessary to apply other tools used in expert systems (Weitzenfeld, Freeman et al., 1990).

The CDM process used in this research occurs in four stages, also known as 'sweeps', with a series of structured probes to re-construct the incident. The multiple 'sweeps' are made to progressively deepen understanding of the challenges faced and strategies employed by decision makers to cope with the situational, environmental and domain demands (Roth, 2008). The four *sweeps* are described below:

Sweep 1: Incident Identification and Selection

This stage is focused on selecting an appropriate incident which would benefit from greater understanding. This will depend on the goals of the project. For example, if CDM is to be used in an incident investigation, then the incident is, obviously, already selected. However, CDM is commonly used to understand more deeply a

work domain without a trigger from a specific incident. In these situations it is recommended to select 'tough cases': those involving non-routine tasks/situations and complex decisions. This is because these tough cases are noted to be more likely to assist in the elicitation of relevant tacit knowledge (Shadrick, Lussier et al., 2005). Furthermore, the participant must be a decision maker or 'doer' in the situation (Crandall, Klein et al., 2006). A review or screening of multiple incidents might be required in order to find one that is appropriate. Once an appropriate incident has been identified the participant is asked to give a brief account of the story from start to end. The participant may need to be guided through the process. Notes are taken whilst the person talks to provide the 'bones' for the subsequent sweeps.

Sweep 2: Timeline Construction and Verification

The second sweep of the incident aims to gain a clear structure of the incident that is refined and verified with the participant. During this sweep the initial account of the incident is expanded. It begins with a merge from sweep 1 where one of the interviewers repeats what they have recorded and understood of the participant's brief account of the incident. The participant is encouraged to correct faults and add relevant information to ensure the account is consistent, accurate and appropriately detailed (Crandall, Klein et al., 2006).

The researchers then construct a timeline of the incident in relevant chunks: distinct occurrences, actions or decisions. The timeline constructed should be visible to the participant. This has been done in the past simply using Post-it™ papers (Wong, Daiper et al., 2003), whiteboards (Riedl, Weitzenfeld et al, 1990) or simply large pieces of paper (Crandall, Klein et al., 2006). Following construction of the timeline, the critical junctures, or decision points, are highlighted to show where a situation could have been understood several ways. The understanding of the participant held at this point, when compared to the alternatives, should effect the eventual outcome (Crandall, Klein et al., 2006). Once the timeline has been constructed and the critical junctures highlighted, the CDM moves to the next sweep.

Sweep 3: Deepening Understanding

In this sweep of the incident the researchers attempt to understand the participant's sensemaking in the situation or, as stated by Crandall, Klein and Hoffman:

“get inside the expert's head and see the world through his or her eyes... What is the story behind the story? Based on the first two steps (the researchers) know what happened... but what did (the interviewee) know, when did they know it, how did they know, and what did they do with what they knew?” (p.72)

To gain this information the researchers sweep over the critical junctures again asking the participant a series of deepening probe questions. The probes used will depend on the event but are generally aimed at determining the information available in a situation, the meaning this information as interpreted by the participant, and the thoughts and issues they provoked. Ideally at this stage, the participant will provide a rich understanding of the event, though occasionally, a participant may be unable or unwilling to share their experience. A regular pitfall is for participants to drift into generalisations. Whilst this might reflect their experience skills and knowledge, it is important that the participant give information on the selected incident. The CDM deepening probe questions, developed by Crandall, Klein and Hoffman (2006) from their experience of the technique, are listed in Table 3.1. These probes are not a complete list of what could be asked, nor are they necessarily relevant in all situations, but rather they provide a starting point for researchers to begin the deepening process.

Sweep 4” “What if” Queries

The last sweep involved in a CDM interview involves the interviewer posing a number of hypothetical changes to the event in the form of 'what if' questions. The participant is asked how their responses would have altered and/or if the outcome of might have changed. This is to gain a deeper understanding of the experience, skills and knowledge of the interviewee. It is also useful in seeing if the information gained is generalizable. The CDM “what if” probes, developed by Crandall, Klein and

Hoffman (2006) from their experience of the technique are listed in Table 3.2. Again, they may not all be necessary in all situations.

Table 3.1: CDM deepening probes used in the 3rd sweep (adapted from Crandall et al, 2006)

Cues	What were you seeing, hearing, smelling, noticing etc.?
Information	What information did you use in making this judgement? How, where and from whom did you get this information? What did you do with the information?
Analogues	Where you reminded of any previous experience? What about that previous experience seemed relevant to this case?
Standard Operating Procedures	Does this case fit a standard or particular scenario? Is this a type of event you are trained to deal with?
Goals and Priorities	What were your specific goals and objectives at the time? What was the most important thing to accomplish at this point?
Options	What other courses of action were considered or available to you? How this option chosen or others was rejected? Was there a rule you were following in choosing this option?
Experience	What specific training or experience was necessary or helpful in making this decision?
Assessment	Suppose you were asked to describe this situation to some else at this point. How would you summarise the situation?
Mental Models	Did you imagine the possible consequences of this action? Did you create some sort of picture in your head? Did you imagine the events and how they would unfold?
Decision Making	What let you know that this was the right thing to do at this point in the incident? How much time pressure was involved in making this decision? How long did it actually take to make this decision?
Guidance	Did you seek any guidance at this point in the incident? How did you know to trust the guidance you got?

Table 3.2: CDM ‘What if’ probes used in the 4th sweep (adapted from Crandall et al, 2006)

Expert Novice	If a novice had been in charge at this particular point in the incident, what type of error
Contrast	might she or he have made and why? Would they have noticed what you noticed? Would they have known to do [key feature]?
Hypotheticals	If [key feature] of the situation had been different, what impact would it have had on your decision/assessment/actions/plans?
Experience	What training might have offered an advantage in this situation?
Aids	What knowledge, information or tools/technologies would have been useful/helped in this situation?

3.1.3.4 Limitations and Reliability

One major limitation of the method is that the interviewer(s) is necessarily affected by what they have been trained to see (Wong & Blandford, 2002). Additionally because only one incident is commonly explored with each participant, the data obtained will only be an accurate representation of the broader system if the disturbances investigated are actually representative of real world scenarios (Wong & Blandford, 2002). Of course, because experts are used then the knowledge elicited may not be valid when novices are involved. However, eventually, with enough experience most persons eventually operate as experts in their specified domain. Therefore, it has been argued that understanding expert reasoning and, if necessary, working backwards to novice reasoning is a valid way to investigate real world complex sociotechnical systems (Hoffman, Coffey et al., 2002).

This can be further complicated as the participant, rather than the researcher, largely determines the situation that will be investigated, making it more difficult to target a single issue. However, this can be seen as a positive, in one sense, as it means that the issues emerge from the investigation rather than a pre-selection of issues that the interviewer assumes are important (Weitzenfeld, Freeman et al, 1990). In a similar way, it also relies on the interviewer to be aware of the influence of the environment on their behaviour. Whilst they may be aware of this, or it can be

elicited, it is not always known, especially if it is beyond their control or observation. Therefore, CDM is better at describing behaviour than causes (Weitzenfeld, Freeman et al, 1990).

Despite these issues CDM has shown strong reliability. Klein investigated inter-coder reliability of CDM by examining the identification of decision point and coding of strategies by different researchers. It was found that agreement on the 29 decision points of the situation varied from 81-100% and coding of strategies at 67%, or 88% with slightly looser criterion (Klein, 1987). Furthermore, as has previously been described, CDM has led to elicitation of knowledge perceived to be useful in various domains. Therefore, whilst it is wise to remain mindful of the noted limitations they do not diminish the potential usefulness of CDM in mining.

3.1.4 Decision Ladder

3.1.4.1 Background

For the information obtained by a CDM to be useful it must be converted into mental models which inform design (Clake, Feldon et al., 2008). Historically, the mental models proposed a normative ideal of decision making. The judgement for a success was that it was able to successfully guide an intervention, such training or decision aids, which reduce departure from the normative ideal proposed. These models were heavily rationalistic where a decision maker identifies a set of options, a way to evaluate the options on multiple dimensions, performs the evaluation, and selects the highest weighted option (Lintern, 2001). These models are described as normative and interventions based on them called analytically based prescription (Lipshitz & Cohen, 2005) . Interventions include such measures as modelling options, option determination and formal prediction of various results.

Critics of rationalist models note that this representation of decision making is often not reflected in reality. The critics of rationalistic models are more interested in explaining what *does* or *did* happen in real life decision-making, especially in time pressured environments where expert judgement is involved (Lipshitz, Klein et al., 2001). It has been argued that in these environments naturalistic models such as RPD model provide more appropriate normative models on which to base

interventions (Cohen & Freeman, 1996). This is principally because they better reflect actual decision making in organisations especially at the level of front line operators (Gore, Banks et al., 2006; Horberry, Cooke et al., 2011). These critics of rationalistic models have commonly turned to CTA methods that use descriptive research where the ideal pattern of decision making is not described. Interventions based on this evidence are termed empirically based prescriptions (Lipshitz & Cohen, 2005).

However, the validity of interventions emerging from naturalistic models and techniques is not without its critics, especially the claims that descriptive research cannot distinguish between 'what is' and 'what ought to be' in a cognitive process (LeBoeuf & Shafir, 2001; Gore, Banks et al., 2006). Decision aids derived from CDM methods, especially those for non-experts, still require validation (Horberry, Cooke et al, 2011). In addition, though it is now accepted that most decisions in organisations are naturalistic, there are still decisions that are better described by rationalistic processes (Lipshitz, Klein et al., 2006). For example rationalistic decision is more likely in such novel situations, when novices are involved or in the absence of time pressure (Randel, Pugh et al., 1996). In these situations the RPD model cannot be used to represent decisions. Therefore, there is an uncomfortable overlap between 'rational' and 'natural' decision models. The Decision Ladder offers a solution as it appears to be the most complete and tested model that can accommodate both approaches.

3.1.4.2 Accommodation of Naturalistic and Rationalistic Decisions

The decision ladder has been demonstrated to accommodate both naturalistic and rationalistic decisions. With regards to naturalistic decision making, there are typically three ways experts move through the RPD model; a simple match of a situation to an action, a variation where a pattern matching loop occurs during problem diagnosis and a variation where a mental simulation loop occurs to test various action strategies. Naikar (2010) has shown that all of these decision types can be accommodated by the Decision Ladder. In practice, Lintern (2011) has recently shown that naturalistic decisions elicited using CDM, that would traditionally

have been represented in the RPD model, can be represented onto a Decision Ladder or series of ladders.

However, Rasmussen's original observations in thermal power stations noted that sometimes people appeared to act spontaneously, similar to NDM, whilst others performed a more detailed rationalistic analysis (Naikar, 2010). The original intention of the Decision Ladder was, therefore, to accommodate both these types of decisions. All of the representations of NDM using the Decision Ladder will not enter a value judgement process that is required in rationalistic decision making. If this does occur it can be represented by Decision Ladder and could not be represented by the RPD model. This broader accommodation of available decision methods means the ladder not only captures what *does* or *should* happen in decision making, but also other possibilities: what *could* happen (Jenkins, Stanton et al., 2011). Therefore, using the Decision Ladder appears more flexible because it can include broader types of decision making strategies than the RPD or rationalistic models.

3.1.4.3 Description of the Method

The Decision Ladder is a model of decision making created by Rasmussen which represents how people make decisions. Rasmussen states that the original ladder is not a model of how decisions are, or should be, made. Rather it is a useful aid for representing decisions (Rasmussen, 1986). It is now most commonly associated with Cognitive Work Analysis (Lintern, 2009) (Lintern, 2009). There are multiple versions of Decision Ladders as it has been iteratively designed to make it more useful and understandable. The version of the Decision Ladder to be used is shown in Figure 3.3. This is the latest iteration by Lintern that has been adapted to better link with NDM models. It is a slight update on the ladder published in the Journal of Cognitive Engineering and Decision Making (2011).

Each arrow represents a cognitive data processing activity – a *process* for short (Vicente, 1999). Each box represents a state of knowledge – a *state* for short. In what is termed 'rational' decision making, the ladder will either go all the way to the top if multiple options are available, possibly including multiple loops, or skip from future state awareness to desired state awareness if only one option is available.

This is roughly equivalent to what is proposed by subjective expected utility theory, where all outcomes that a decision maker can identify are expressly included in decision-making.

The Decision Ladder can be divided into three main sections:

1. **Situation Awareness:** At the bottom left of the ladder the decision maker is gaining information from the environment and beginning to anticipate the future changes.
2. **Value Judgement:** At upper section of the ladder the decision maker is consciously scrutinising possible general courses of action.
3. **Planning and Execution:** The bottom right of the ladder the plan of action is formed and ultimately executed.

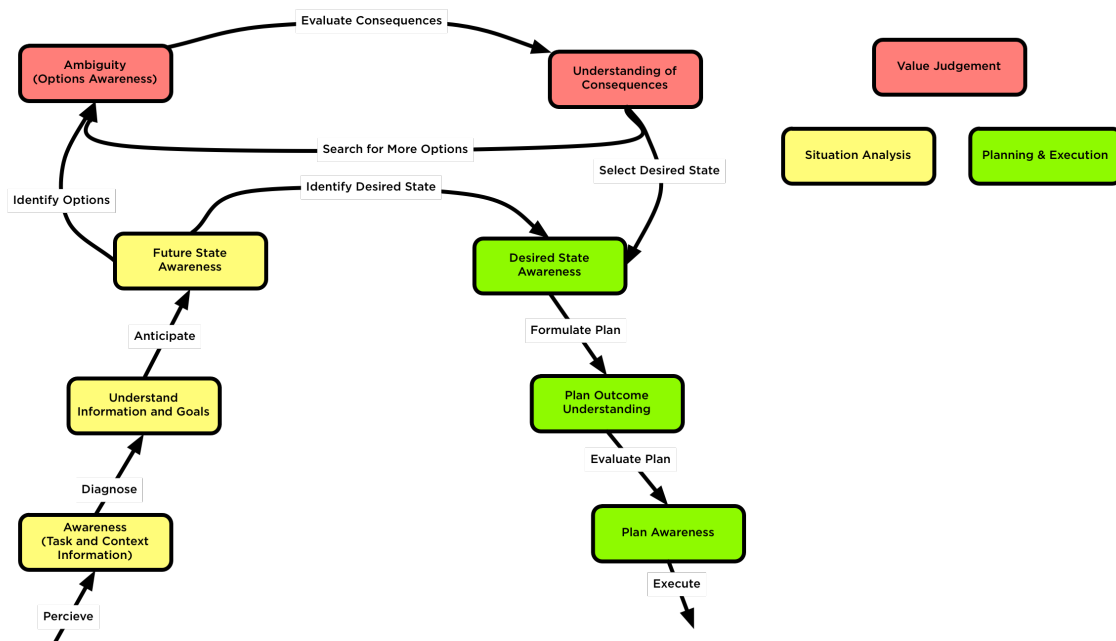


Figure 3.3: Lintern’s Version of the Decision Ladder with the three sections highlighted

The theory of the Decision Ladder is that it is possible for a decision making process to go all the way up the ladder. When this occurred it would be seen as a ‘rational’ decision path very similar to the style of decision making described by Subjective Expected Utility theory. This would be most likely to occur in novel situations

experienced by non-experts. However, when the ladder is used to represent real word decisions, it is noted that ‘jumps’ across the ladder occur. In the previous Decision Ladders there are two types of jumps: shunts and leaps. These can be seen in Figure 3.4. Shunts connect a process to a non-connected state. Leaps connect two states together (Jenkins, Stanton et al., 2010). A direct transition between states implies a cognitive process, thereby meaning that a jump *is* a cognitive process (Lintern, 2011).

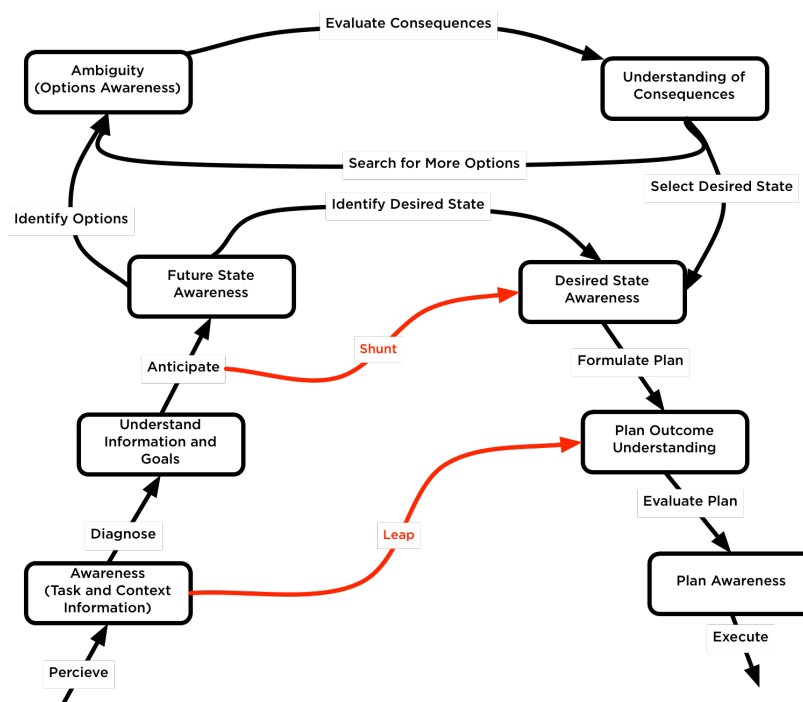


Figure 3.4: Example of a shunt and a leap on the Decision Ladder (adapted from Lintern, 2011)

Leaping from a process to a non-connected state is disconcerting as it implies connecting a process with a new process, breaking the model of the Decision Ladder. Therefore, most recent use of the Decision Ladder only uses leaps, allowing the user to describe a cognitive state in-between. As there is only one type of cognitive translation occurring, there is no need to term the process a ‘shunt’ but simply a jump. These jumps have been termed shortcuts or state transitions (Lintern, 2011). These jumps represent the heuristic transitions that are expected to more readily occur with experts in familiar circumstances. Two jumps can be seen on

Figure 3.5. Whilst the jumps on the figure are forwards Naikar showed that to represent some NDM patterns on the Decision Ladder backwards jumps must be used (Naikar, 2010). Backwards jumps were not included in previous uses of the Decision Ladder.

In order to code the jumps, each process has been given a number. This coding of the processes is a novel innovation to make the Decision Ladder easier to use. For example a jump from ‘future state awareness’ to ‘plan outcome understanding’, with a presumed cognitive process in between, can be shortened to the annotation 3-7. Similarly, a jump from one state to a previous state can be coded by the order of the numbering. For example a jump from ‘future state awareness’ to ‘understand information and goal’, which could occur if a decision maker realises that they need more information to predict a likely future state, would be represented as 4-3. ‘Jump-codes’ is proposed as an appropriate term for this annotation. A jump between states can also be easily drawn on an actual ladder and made into a small representative pictogram. The numbering system for states and an example of a jump with the associated pictogram is illustrated in Figure 3.6.

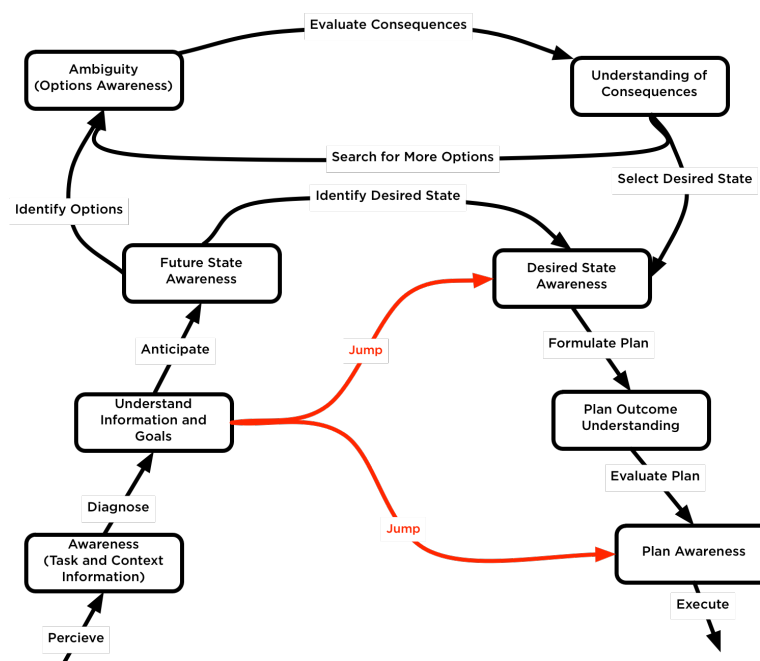


Figure 3.5: Jumps on the Decision Ladder (Adapted from Lintern, 2011)

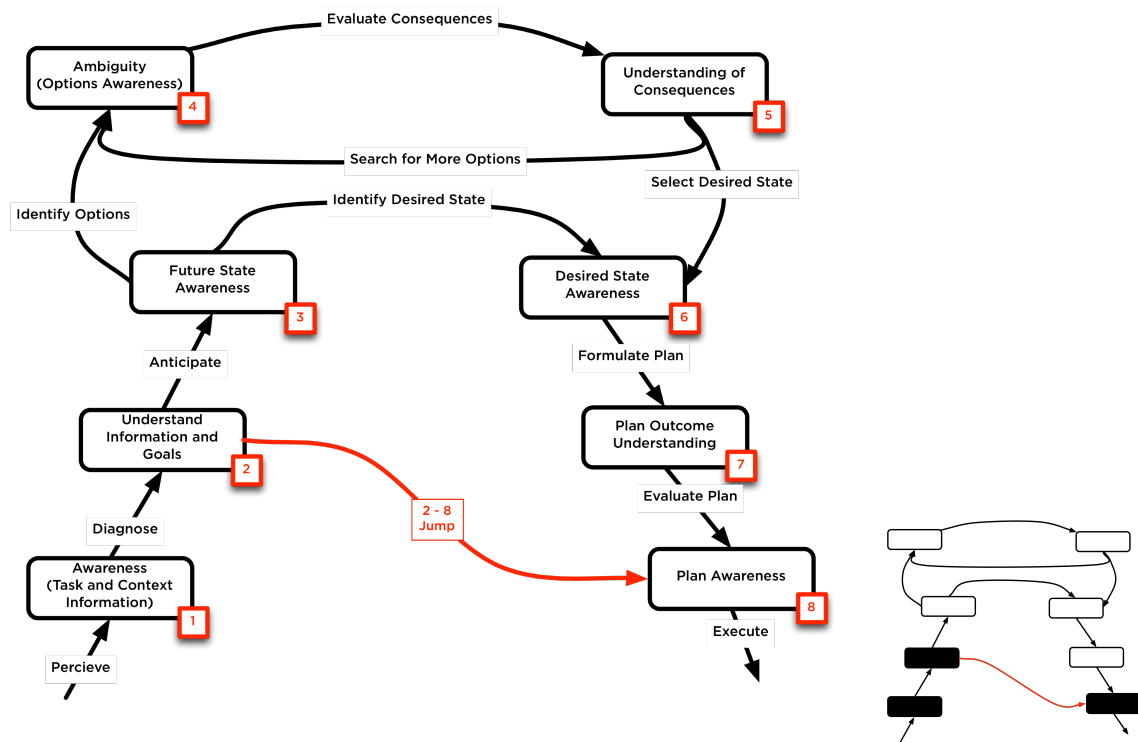


Figure 3.6: Numbered Cognitive States with a Jump coded by numbers
 (Adapted from Lintern, 2011)

3.1.4.4 Design Implications

Ultimately, the Decision Ladder will prove useful addition to CDM in the domain of mining equipment safety if it positively alters risk controls, especially those that are based on equipment design or modification. Currently, CTA has been noted to be primarily a domain of research and rarely used by designers (Clarke, Feldon et al., 2008). This is also true of the Decision Ladder.

The specific leverage of CTA in the design of systems has been termed Decision Centred Design. In this process CTA is used to elicit how key decisions are made, and representing these for use consideration during design (Horberry, Cooke et al, 2011). In this respect it has been described as an adjunct version of user-centred design, where the focus is specifically on the *decisions* of users (Hoffman, Feltovich et al., 2002).

The originators of Decision Centred Design give an overview of the process and included the following stages:

1. Analysis
 - a. Background preparation and domain familiarisation
 - b. Observations and knowledge elicitation using CTA
 - c. Definition of decision requirements and decision strategies
2. Design
 - a. Transformation of decision requirements and decision strategies into design concepts
 - b. Development of key design recommendations
3. Test and evaluation
 - a. Development of evaluation scenarios and contexts
 - b. Development of context-sensitive metrics
 - c. Development of real-world outcome evaluation criteria

The developers of the technique, however, do not strictly state what is to occur inside each of these stages, stating that it is difficult to provide a 'cookbook recipe' for the method (Hutton, Miller et al., 2003). Decision Centred Design has been described more as an approach rather than mechanical procedure (Klein, Kaempf et al., 1997). Therefore, the representation of decisions elicited using CTA methods is not tied to particular model of decision making. Rather the model that best suits the purpose should be used. The model of representation used will be important in the eventual success.

The previous section noted that the Decision Ladder clearly reveals cognitive shortcuts and, in the process, other alternative routes. It is for this reason that Elix and Naikar (2008) claim that the Decision Ladder is especially suited to use in design as it can not only represent past decisions as they occurred, but also alternative paths of future decisions. This consideration of alternative decision making is not accommodated by either the rationalistic models or the RPD model as these were largely developed for descriptive purposes. By showing all possible routes the ladder clearly reveals a modelled path of the remaining decision including state, processes and heuristic jumps. After understanding this, the various options to

support decision making can be considered. An intervention could improve the speed and accuracy of the current path. It could alternatively aid or force a user to take another path, whether that be more rationalistic or making heuristic jumps across the current decision path. It may also automate some of the decision making as the Decision Ladder can accommodate decision making by non-human elements of the system. The ultimate interventions may be highly technological or simple. As Lintern states:

“Whether any form of technological support is desirable for any particular cognitive state or process will depend largely on whether that state or process offers a particular cognitive challenge that could be eased by the form of intervention being proposed... The decision centred perspective promotes judicious application of knowledge elicitation tools to identify problem areas in current work practices and to isolate leverage points that offer high value (but often low cost) interventions” (2001, p.310).

Lintern argues that every different state or process on the Decision Ladder could be supported by some form of technology, process or training (Lintern, 2011). Figure 3.7 shows suggested categories of support at some states and processes on the Decision Ladder. This can be used to design how information can be given to decision makers in a meaningful, structured and timely manner (Jenkins, Stanton et al., 2010). By targeting an intervention in a modelled decision pattern, it is hoped that the interventions will have an increased likelihood of positive effect and wasteful, perhaps even harmful, interventions are avoided.

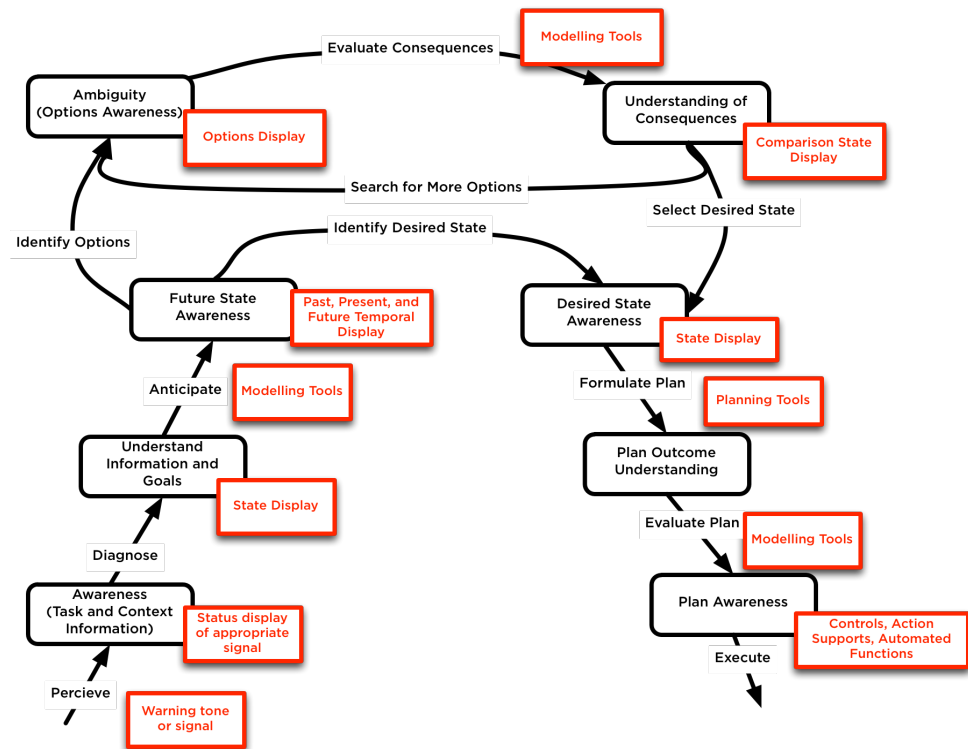


Figure 3.7:
Suggested categories of support for some stages and states
(adapted from Lintern, 2011)

3.2 Method

3.2.1 Scope and Goal

Following CDM's successful use in other domains, it was envisaged that capturing and analysing information related to critical incidents during the operation of surface mining, and the decision making around these incidents, would result in valuable new information for the industry. The initial goal was therefore to investigate if CDM *could* provide such information. To help establish if CDM would be of value, it was compared to the results of other current incident investigation methods. The secondary goal was to investigate if the Decision Ladder provides an effective representation of the elicited knowledge that aids design. This is not only to understand the decisions made, but also to aid the evaluation and design of future interventions.

3.2.2 Participants

Data were collected from nine participants during two visits to surface coal mines in central Queensland, Australia. Eight of the interviews were for specific incidents used as an accident investigation method. One final participant was interviewed about an error prone task to trial the predictive power of the method. The participants were experts in the work domain (i.e. experienced mining equipment operators) but who had previously been involved in an incident. It was a requirement for the research that the participant be an active decision maker in the incident. The interviews all involved mobile equipment operators who were operating equipment at the time of the incident.

3.2.3 Procedure

3.2.3.1 Decision Identification and Analysis Procedure

The research employed the 'classic' CDM method, as outlined above, with slight adaptations, where required, to the mining context (e.g. in the terminology used). The CDM interview process was undertaken by two researchers. The interview took up to two hours, though significantly more time was needed for preparation and post-interview analysis. It took place in an office or other location that was suitably quiet and largely free of interruptions. At all times the participants were encouraged to draw diagrams on whiteboards as it was quickly established that this helped their expression (see bottom left of Figure 3.8). They often needed to be guided through the process and directed towards talking about other aspects of the task which appeared particularly relevant to the purpose of this work.

In the first stage of CDM, the participant described the incident to one of the interviewers, who provided prompts and questions for clarification, whilst the other interviewer took notes on a laptop computer. It was a requirement that the participant had been a decision maker or 'doer' in the incident. A review or screening of multiple incidents was often required in order to find one that was appropriate for the purpose of this research. Once an appropriate incident had been identified, the participant was asked to give a brief account of the story from beginning to end.

In the second stage of CDM, the interviewer who was taking notes repeated the incident back to the operator, who provided clarification and additions. At this stage the other interviewer started to 'chunk' the incident on a nearby whiteboard into distinct actions, occurrences or decisions to create a timeline. Chunking the incidents on the whiteboard proved to be less distracting than using Post-it™ notes. The participant was encouraged to correct errors and add relevant information to ensure the account was consistent, accurate and appropriately detailed. Following construction of the timeline the critical junctures, or decision points, where a situation could have been understood several ways or altered, were identified by the interviewers and circled on the timeline (see bottom right of the Figure 3.8).

In the third and fourth stages of CDM, both interviewers asked probe questions modified from the list above. At each stage questions were asked repeatedly until it was clear that no new information would emerge. The probes used depended on the event but were generally aimed at determining the information available in the incident, the meaning of this information as interpreted by the interviewee and the thoughts and issues they provoked. At this stage the participant usually gave a rich understanding of the event, though occasionally, they may have been unable or unwilling to share their experiences. A regular pitfall was for participants to drift to generalisations and, whilst this might reflect their experience, skills and knowledge, it was important that the participant gave information on the selected incident.

3.2.3.2 Decision Representation Procedure

Following the interview, the key decisions identified were represented on the Decision Ladder. The represented decision, as the other elicited knowledge, was then used to generate design decisions. This was done using the information recorded in the CDM, especially the deepening probes, and expert judgement. The use of expert judgement is the established method with the Decision Ladder (Jenkins and Salmon, 2009) which has some emerging evidence of inter-rater reliability (Rehak, Lamoureux et al., 2006). In this study, the scope was limited to trialling the representation of the method to determine if it appeared to aid design decisions.

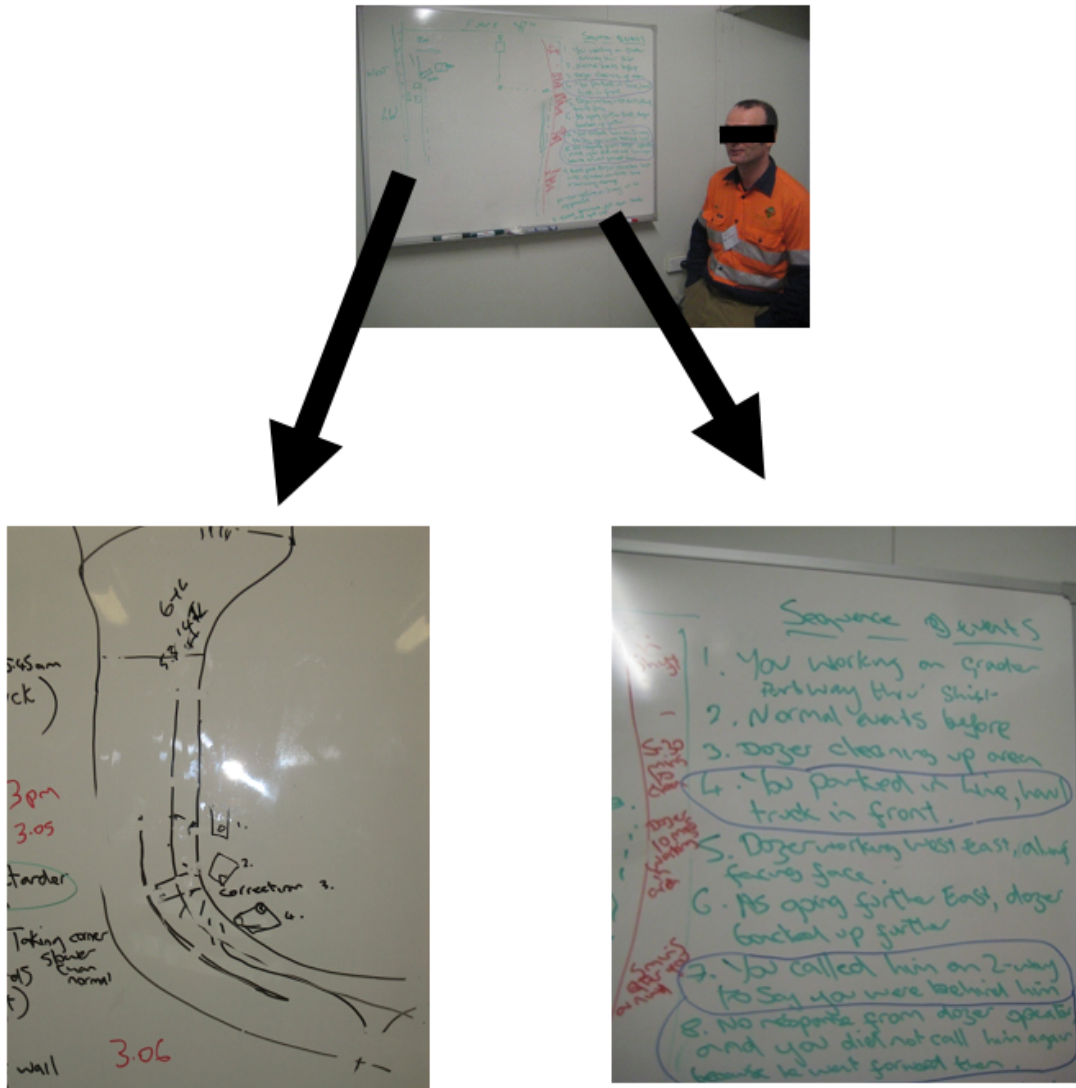


Figure 3.8: Whiteboard use for sketching, timeline construction and key decision selection

3.2.4 Comparison to Implemented Method

In addition to purely analysing the data for the nine incidents, in six a formal local site incident investigation had previously taken place using the standardised Incident Cause Analysis Method (I-CAM). I-CAM is a prevalent incident investigation method used in the Australian mining industry (De Landre, Gibb et al., 2006). It is based on James Reason's models of organisational accident causation (1997) and Jens Rasmussen's skill/rule/knowledge model of human error (2005). I-CAM provides a classification system for various local or latent factors that may be involved in an incident (De Landre, Gibb et al., 2006).

Whilst there is some overlap between using CDM with the Decision Ladder and I-CAM, the latter does not include a structured interview process or detailed model for representing decisions. Therefore, the findings of I-CAM investigation were reviewed to determine if any key points identified by the structured interview CDM were omitted. This was seen as possible because whilst I-CAM does include an interview stage, it is only guided by broad principles rather than the formalised process to elicit specific knowledge of key decisions offered by CDM. Additionally, the recommendations of I-CAM were reviewed to determine if they differed from those that emerged after using the decisions ladder. The judgement of success in this case is that the application of CDM and the Decision Ladder was able to successfully elicit information and/or design changes that were not contained in the original analysis.

3.3 Results

3.3.1 Detailed Case Study

To illustrate the detail of applying the process, an incident where a haul truck drove into an overhead chute for soil that has been rejected from the process plant is explained in detail. A flowchart of the incident is shown in Figure 3.9. This flowchart is the chunks created from CDM sweeps 1 and 2. This shows the major stages of the event, in text boxes, and the points where risk controls were defeated, as rectangles – after boxes 3, 6, 11 and 13.

The key decision areas were noted to be the electrician deciding not to test the repair and the driver commencing driving with the tray up, forgetting to pull the lever that brings the tray down. These decisions were noted to occur just prior to the second last and last potential risk controls being defeated. These key decision points were further explored in Sweep 3.

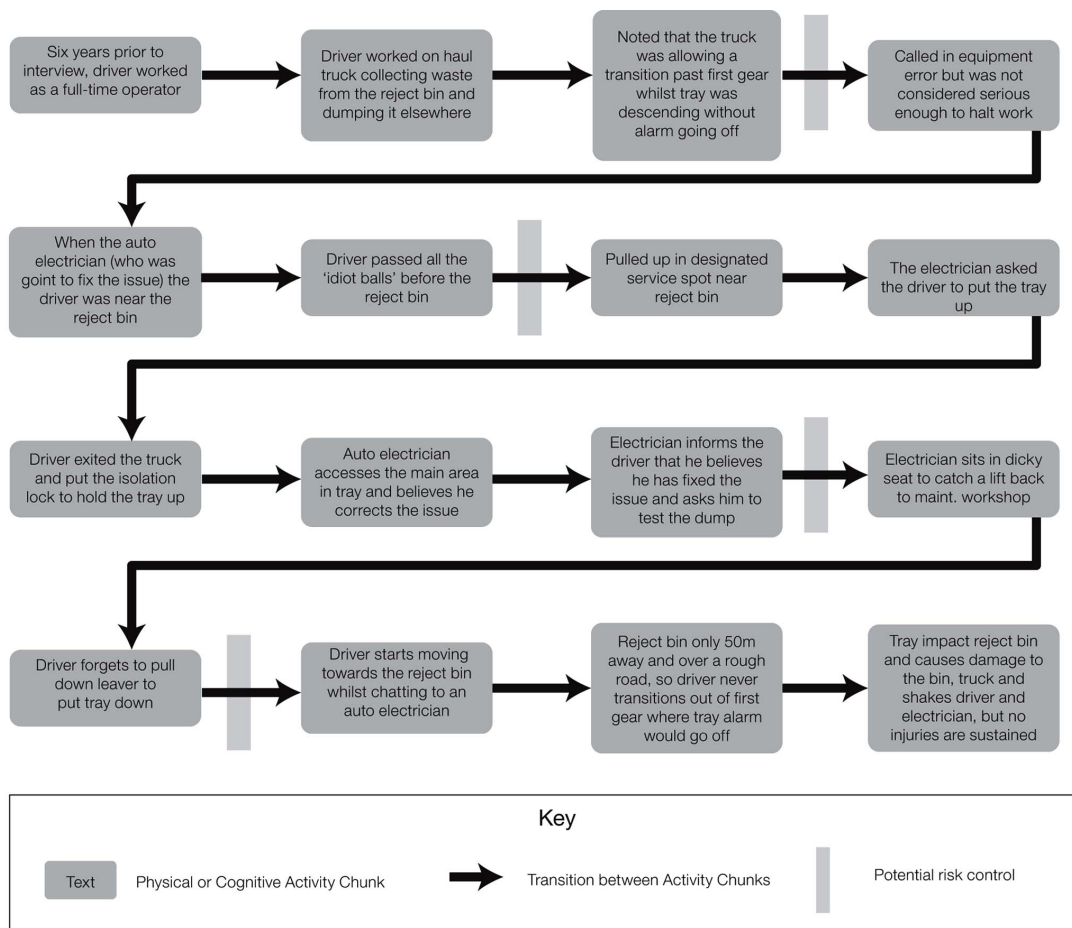


Figure 3.9: The timeline of the incident with points of defeated risk controls

Notable information, none of which was subsequently found in the I-CAM report, included:

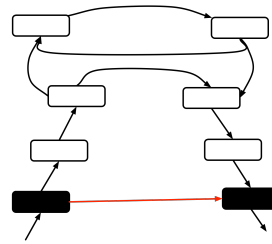
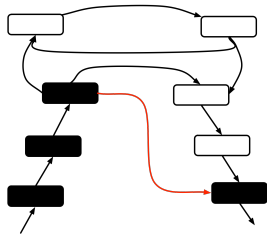
- The driver had rarely previously started the truck with the tray up.
- ‘Idiot Balls’ were placed around the mine, but the park up bay was past the last idiot ball. These are large plastic balls dangling from wire that would be hit if equipment is entering an area above the height were it will strike equipment or power lines.
- The display for ‘tray up’ was only visual and was possibly obscured by sun glare.
- The driver was talking to the electrician during the drive.
- There was no visual feedback to the driver that the tray had, or had not, started lowering.

Similarly, example findings from the “what if” inquiries (Sweep 4) that were not noted in the previous I-CAM investigation report were:

- An audible signal might have alerted the driver to the fact that the tray was raised.
- If the driver was not a friend of the electricians, the driver may have noticed the tray (due to him being partially distracted by their conversation).
- If the park up bay was further from the reject bin or the road conditions were better, the driver would have reached 8km/h and set off the tray up alarm.

Following the CDM the two decisions were mapped on the Decision Ladder. The decision not to test the tray involved a jump from ‘future state awareness’ (3) to ‘plan awareness’ (8) as depicted by Figure 3.10. This was determined because the electrician appears to have determined that the problem was fixed, predicting a future state, and then jumped to driving away without any evaluation or further thought. It then appears that any intervention would be best to force the decision to go through more evaluation actions after a breakdown of this type. An infield post maintenance checklist for the driver and the maintainer to complete is suggested to force the decision through the stage ‘plan evaluation’ on the decision ladder.

The decision by the driver not to push the tray up lever appears to have been almost automatic. The operator performed exactly the same movements that he would in a normal start up. This indicates a skill based behaviour jumping straight from ‘Awareness (Task and Context Information)’ (1) to ‘plan awareness’ (8) as depicted in Figure 3.11. Therefore, it is suggested that any intervention would help a driver perceive that the situation is abnormal and the tray is up. The design suggestion is to insert a tone to indicate that the tray is up on start-up and continue as a warning until it is lowered. Therefore, in this case CDM was able to uncover extra information not obtained in the current incident investigation and the decision ladder was able to successfully represent key decisions in a way that aided design suggestions.



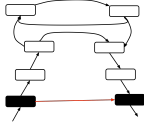
**Figure 3.10: 1st Key Decision. 3-8 jump. Figure 3.11: 2nd Key Decision. 1-8 jump
Electrician does not check fault is fixed. Driver does not lower the tray**

3.3.2 Decision Analysis and Representation Summary Tables

A summary of the data collected from the nine CDMs is presented in the following tables. This includes the description of the incident, the main notes and findings from CDM and the key decisions, including a representation on the decision ladder, and design suggestions. Overall, all of the trials were able to uncover key decisions and environmental influences. This could then be translated into Decision Ladders and novel and specific design suggestions. Extra information was revealed in each of the six incidents where an investigation report was available directly or through operator account.

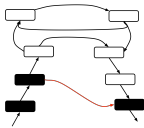
Incident 1:

Uncontrolled drop of shovel bucket that collided with a reversing haul truck.

Critical Decision Method Summary			
Short Description from CDM	Main CDM Findings		
<p>Interviewee was operating a shovel and loading haul trucks when there was an uncontrolled drop of the bucket.</p> <p>At the time a haul truck was backing under the shovel.</p> <p>The bucket dropped just before the haul truck was under the shovel but it could not stop before reversing into it.</p> <p>Had the drop happened later it could have fallen into the tray of the haul truck.</p>	<p>There is a tendency for the bucket to 'drift' downwards if not actively pulled back. This might have caused the operator to pull back on the lever when the bucket fell, rather than pressing the emergency stop button.</p> <p>Operator noted that a fault error displayed on the screen that he had not previously seen, and was not in the instruction manual.</p>		
Decision Representation and Design Suggestions			
Major Decision	Jump Code	Jump Icon	Suggested Design Interventions
<p>When the bucket started to fall the operator pulled back the lever rather than press emergency stop</p>	<p>1-8.</p>		<p>Consider placing an emergency stop function on the shovel controls/ joystick rather than as a separate button.</p>
	<p>Rationale</p>		
	<p>Decision was immediate physical action in response to the environment.</p>		
Comparison to I-CAM			
Compared to I-CAM	Findings compared with I-CAM		
<p>YES</p>	<p>The I-CAM report <i>does not</i> note how the driver attempted to halt the bucket.</p> <p>Error message that the driver claims to have seen is not noted.</p> <p>It also has only a very short description of the incident and one word answers to I-CAM questions, which would make it difficult to ascertain a pattern should a similar event reoccur.</p>		

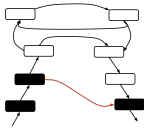
Incident 2: Rollover of bulldozer whilst pushing/cleaning overburden (top soil)

Critical Decision Method Summary	
Short Description from CDM	Main CDM Findings
<p>Interviewee was a trainee bulldozer driver pushing back overburden alongside a trainer operator.</p> <p>The trainer was working on the overburden in another bulldozer and paying only little attention to the trainee.</p> <p>At the point of the rollover he was working in a 'cut' directly next to the trainee and creating a lower level.</p> <p>Trainee was attempting to reverse straight back, but was actually going at an inaccurate angle and the vehicle fell into the trainer's 'cut', causing it to rollover onto its roof.</p>	<p>The lack of awareness by the trainee that he was not reversing in a straight line was a key cause of this incident.</p> <p>Factors increasing the likelihood of this error included the limited rear vision, the lack of light (night shift) and perceived pressure to keep up with the trainer's pace.</p> <p>The trainer's lack of intervention (e.g. by radio communication) in this was also a key cause.</p> <p>Additionally, having another bulldozer working in close proximity created the conditions (i.e. the 'cut') where the bulldozer could roll.</p>

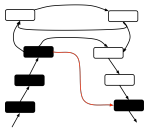
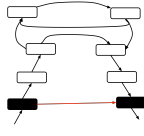
Decision Representation and Design Suggestions			
Major Decision	Jump Code	Jump Icon	Suggested Design Interventions
<p>The trainee bulldozer operator decides that he needs to reverse, looks over his shoulder to diagnose the situation and then reverses.</p>	2-8		<p>A reverse facing camera to let the trainee see out the rear.</p> <p>Coloured light to the ground out of the rear to indicate heading in relation to other objects.</p>
	Rationale		<p>Raised cab position in future models to improve view to rear.</p>
	<p>After 'diagnosing' the state of the ground the trainee immediately reversed.</p>		<p>Potential to use remote control.</p>

Comparison to I-CAM	
Compared to I-CAM	Findings compared with I-CAM
<p>YES</p>	<p>The supervision of the trainee was the key factor noted in the I-CAM and the practice of having a trainer work next to a trainee was ceased.</p> <p>Key factors relating to the error reversing <i>were not</i> identified, such as the low lighting, perceived time pressure and lack of vision out of the cab.</p>

Incident 3: Fire at a fuelling station

Critical Decision Method Summary			
Short Description from CDM		Main CDM Findings	
<p>The fire occurred at the fuelling station when the interviewee was working as an offsider (helper) to a fuelling serviceman.</p> <p>Sometime after connecting a 'wiggins fitting', which automatically fills the fuel station using the engine of the pump, both participants noticed that fuel was spraying out of the top of the fuel station.</p> <p>This fuel landed on the top of the turbocharger of the refuelling truck and caught fire immediately, at which point both the serviceman and the interviewee fled the area and a large fire ensued.</p>		<p>The serviceman attempted to cancel pumping using the control system, indicating that an emergency stop was not fitted or available near the operator's position. (The interviewee thought this was likely, but it would require confirmation.)</p> <p>Vehicle movement was isolated using the park break. In another case this might have prevented the vehicle being moved which would have stopped the fuel hitting the fire.</p> <p>There was no protection/barrier between the hot engine and the fuel landing on it from the pump.</p>	
Decision Representation and Design Suggestions			
Major Decision	Jump Code	Jump Icon	Suggested Design Interventions
<p>Potential Error in truck placement recognises goals but skips anticipation of future state (failure) and jumps to plan awareness.</p>	<p>2-8</p>		<p>Place greater protection/guarding over the turbocharger.</p> <p>Place an emergency stop on the pump controls.</p>
		<p>Rationale</p>	
		<p>The driver 'diagnoses' a flat area to park near the fuel station and then immediately parks.</p>	
Comparison to I-CAM			
Compared to I-CAM	Findings compared with I-CAM		
<p>YES</p>	<p>The I-CAM noted a corrective action was fit a 'deflector' on the fuel tank to assist in preventing fuel heading in the direction of the pumping vehicle. Additionally, a cover was placed over the engines.</p> <p>The difficulty in cancelling the fuel flow, and the emergency stop, was <i>not</i> noted.</p> <p>The potential issue of unengaging park brake isolation in an emergency was <i>not</i> addressed.</p>		

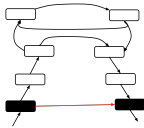
Incident 4: Drove Haul Truck with Dump Tray Up Striking the Reject Bins

Critical Decision Method Summary			
Short Description from CDM	Main CDM Findings		
<p>Whilst working as a haul truck driver the interviewee noticed that after dumping a load and driving away from an area whilst the tray descended the truck was able to shift up to second gear and pass 8km/h without an alarm sounding. Shifting up gears should be prevented automatically and an alarm set off if the truck passes 8km/h without the tray fully descended.</p> <p>The driver called maintenance to notify them of the issue. After some time they notified him that an electrician was available and to park the truck. The driver did this on his way collect a load from the reject bin; an overhead chute which transfers waste from the process plant into the truck.</p> <p>The electrician worked on the issue, thought it was solved, and sat in dicky (spare) seat to catch a ride to the maintenance shed. The driver forgot to pull lever to take tray down, the alarm does not sound, as the issue had not been fixed or speed not yet exceeded 8km/h, and the upright tray strikes the reject bin.</p>	<p>The reject bin is surrounded by 'idiot balls': large balls on wire that would normally be contacted before entering the area of the reject bin if a tray is in the upright position. However, the park up bay that the driver selected was past these idiot balls.</p> <p>The electrician felt he had fixed the issue of the lack of tray alarm, but this was not tested or the test was accidentally missed. Other than the tray alarm, there may have been a display showing the driver that the tray was in the upright position.</p> <p>The alarm may actually have been working but the truck not at 8km/h before striking the reject bin.</p> <p>The driver and the electrician knew each other and were friendly. They may have been distracted whilst chatting leading to the above oversights.</p> <p>It is extremely unusual for a driver to start a truck with the tray in the upright position. Therefore, the automatic pattern of behaviour on start-up does not include putting the lever to bring the tray down. The driver said he performed 'exactly what I normally do'.</p>		
Decision Representation and Design Suggestions			
Major Decision	Jump Code	Jump Icon	Suggested Design Interventions
<p>Decision error by the electrician not to test the tray, assuming that it worked. He had awareness of the future state but didn't appear to evaluate the plan of action before acting on the plan to drive.</p>	3-8		<p>Add a maintenance checklist for the driver and the maintainer to complete following jobs in field to be reviewed by the driver.</p>
Rationale			
The electrician anticipated the likely fix but did not consider any other options.			
<p>The driver made a decision error to start driving with the tray up. The driver started to drive, not thinking there would be issues but perhaps checking for them. He reports to have viewed dashboard indicators and not seen the tray up indicator.</p>	1-8		<p>Move park up bay the other side of idiot balls.</p> <p>Insert a tone to indicate that the tray is up on start-up and continue as a warning until it is lowered.</p>
Rationale			
When the driver was informed of the fix he immediately acted to start the truck.			
Comparison to I-CAM			

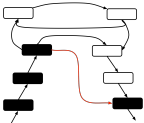
Critical Decision Method Summary

Short Description from CDM	Main CDM Findings
Compared to I-CAM	Findings compared with I-CAM
YES	<p>The I-CAMs corrective actions <i>were</i> re-enforce the need for walk around inspections, the installation of sacrificial devices close to the reject bin to soften/lessen collisions. The I-CAM <i>did not</i> note that the roadway was designed such that a park-up bay was past the 'idiot balls'.</p> <p>I-CAM <i>did not</i> investigate how the driver may have missed pulling the lever to lower the tray. However, the CDM found it was probably because he usually does not pull the lever at start-up and preformed his usual start-up movements whilst talking to the electrician.</p>

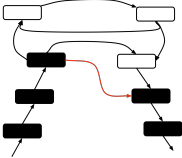
Incident 5: Rollover of troop-carrier

Critical Decision Method Summary			
Short Description from CDM		Main CDM Findings	
<p>Rollover occurred on a 10% grade ramp. Just prior to the rollover a water truck had watered one side of the ramp.</p> <p>Driver was moving off the 'rough' road and skidded when one side of the vehicle hit wet but hard and slippery clay.</p> <p>Vehicle had 4-wheel-drive but was engaged in 2 wheel drive at that time.</p> <p>The vehicle was not exceeding the designated speed limit.</p>		<p>The watering of the ramp was an important primary causal factor.</p> <p>Subsequently, the judgement of the road conditions and speed was an important causal factor in the rollover.</p> <p>This was, potentially, made more likely by the type of vehicle and non-engagement of 4WD.</p>	
Decision Representation and Design Suggestions			
Major Decision	Jump Code	Jump Icon	Suggested Design Interventions
<p>It appears that the driver was reacting to the rough road and almost automatically moved to the other side of the road, moving straight from awareness to plan awareness or understanding the issue and to plan awareness.</p>	1-8		<p>Review the skid/steer/stability systems of the troop carriers.</p> <p>Introduce GPS speed monitoring systems.</p> <p>Review watering and road management strategy – the road may have been too wet.</p>
	Rationale		
		<p>The driver felt the rough road and automatically responded by moving towards smoother road.</p>	
Comparison to I-CAM			
Compared to I-CAM	Findings compared with I-CAM		
<p>Results of I-CAM reported by interviewee, but not confirmed in writing.</p>	<p>Main result of the I-CAM was to re-write watering policy on ramps, changing from continuous to spot watering. Input of troop carrier factors <i>appears overlooked</i>: such as speed, driver judgement and the engaging 4WD.</p>		

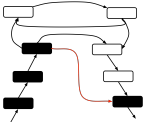
Incident 6: Collision between Bulldozer and Grader

Critical Decision Method Summary			
Short Description from CDM		Main CDM Findings	
<p>A grader, driven by the interviewee, was parked in a line of trucks waiting for a shovel load, meaning that the grader could not move significantly.</p> <p>The bulldozer that was cleaning up the face where the shovel had been backed to within 10-20m of the grader. At this time the grader operator radioed the bulldozer operator and at the same time the bulldozer moved forwards.</p> <p>The bulldozer subsequently reversed again, to make the next cut. As the bulldozer reached the same zone the grader operator did not radio the bulldozer operator believing the previous radio contact had made the bulldozer operator aware of his location.</p> <p>However, the bulldozer operator had never seen the grader and the fact he moved forwards on the previous radio call was a coincidence.</p>		<p>The grader operator perceived that the bulldozer operator had heard him because of the timing of change in direction. But this turned out to be a coincidence.</p> <p>The bulldozer involved had limited rear vision which likely caused the inability to see the grader even though it was parked directly behind the bulldozer.</p> <p>The bulldozer also has significant noise. This can mask radio calls, which was likely in this case.</p> <p>The design of roadways and vehicle separation may have also played a role.</p>	
Major Decision	Jump Code	Jump Icon	Suggested Design Interventions
<p>The decision to consider the bulldozer operators movement away on radio as a receipt of the call, when in fact it was coincidental.</p>	3-8		<p>Vehicle proximity detection or collision avoidance systems.</p> <p>Replace/modify the radio system in the bulldozer to make it more audible (e.g. wireless headset).</p>
	Rationale		
<p>The grader operator radioed was the bulldozer operator anticipating had not seen him – the only action available. However, on movement away the no other options were considered.</p>			
Comparison to I-CAM			
Compared to I-CAM	Findings compared with I-CAM		
<p>Results of Investigation reported by interviewee, but not confirmed in writing.</p>	<p>The interviewee noted that the investigation attributed the cause of the accident to be primarily due to lack of confirmation that a radio call had been heard. The CDM investigation found that the incident was much more complex, and continued radio calls by the interviewee was unlikely to have prevented the collision. No design suggestions appear to have been considered, let alone noted or implemented.</p>		

Incident 7: Engine Fire in Digger

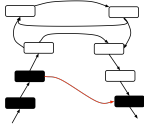
Critical Decision Method Summary			
Short Description from CDM		Main CDM Findings	
<p>Machine was an older model with existing issues. Operators stated that the engine was 'surging' during driver 'hot seat' change.</p> <p>At this stage, a general/informal inspection was conducted for 'something out of the ordinary'. However, a driver would not necessarily know the specific cause for surging- it is up to the judgement of the operator to notify maintenance.</p> <p>Operator continued to operate the equipment after the fire began, as it was at the rear of the machine and not visible to the driver. He was notified of smoke by a haul truck driver – had this not occurred the incident could have been significantly worse.</p> <p>In this case he manually pressed the fire suppression immediately because of the urgency conveyed by the driver. Usually operators would not press the fire suppression unless they saw flames, as it was known to be costly. Newer equipment automatically sets off fire suppression on smoke/fire detection.</p>		<p>The driver of equipment must informally check equipment in the field, making judgements on the seriousness of issues. This is solely based on their experience and instinct.</p> <p>The communication between equipment operators can be key to identifying if smoke is abnormal and the presence of fires in their early stage.</p> <p>The high financial cost of falsely pressing the fire suppression system does influence the operator's decision to engage the system.</p>	
Decision Representation and Design Suggestions			
Major Decision	Jump Code	Jump Icon	Suggested Design Interventions
<p>The positive decision to press the fire suppression was an unfamiliar situation seemingly requiring more formal cognitive processes of understanding. However, he didn't have to formulate a plan as only one was available.</p>	3-7.		<p>In this case, the design decision already exists: automatic fire suppression systems.</p> <p>This incident indicated that situations could exist where the digger operators could react too late to a fire if it is not noticed by another mobile equipment operator.</p> <p>This supports the implementation of automatic systems.</p>
		Rationale	
		<p>The decision included some interpreting of the meaning of smoke detected by the haul truck driver. The driver did not need to go through a cognitive process to determine that fire was unwanted, jumping over identification of desired state. The only option considered was to press the fire suppression. He indicated he paused to consider the financial consequences releasing the system indicating the plan was evaluated before enacted.</p>	
Comparison to I-CAM			
Compared to I-CAM	Findings compared with I-CAM		
<p>No. No I-CAM available</p>	<p>_____</p>		

Incident 8: Loss of control of haul truck down a ramp

Critical Decision Method Summary			
Short Description from CDM		Main CDM Findings	
<p>The loss of control took place on a wet ramp in rainy conditions. The operators had been discussing the conditions, and whether they warranted 'parking up'.</p> <p>Loss of control took place when the vehicle was unloaded it descending the ramp on approximately the 30</p> <p>Usually a slip is more likely when descending unloaded, and whilst a driver may notice some issues when ascending loaded they are generally committed to an entire run once loaded.</p> <p>The road was 'cambered, seemingly encouraging higher speeds to the interviewee driving the truck.</p> <p>The driver skidded when going around the corner, and ended up facing 'up' on the down side of the ramp having spun approximately 180-270 degrees.</p>		<p>The judgement of when rain causes the roads to become dangerous is a key decision made by the team. This decision is not black and white and would have external influences, such as production pressure/competition.</p> <p>The misjudgement of safe speed, set by the auto-retarder, down a ramp was a key cause of the accident worthy of further investigation.</p> <p>The roadway design, with a ramp that included a banked corner, could have also been a cause of the accident.</p>	
Comparison to I-CAM			
Major Decision	Jump Code	Jump Icon	Suggested Design Interventions
<p>The decision not to park up seems like it is a 5-8 jump. The decision gets all the way to a value judgement of the environment, but in the absence of an overriding reason, with all incentives to keep productions going, not to halt they decide to continue.</p>	<p>3-8</p>		<p>Feedback from the tire grip/spinning could be used to inform the driver.</p> <p>Centralise the park up decision to a person who has access to weather information and contact to drivers.</p>
Rationale			
<p>The decision appeared to involved repeated and conscious evaluation of the situation, involving steps 1-3, with the decision not to park up jumping directly from an anticipation of the future state.</p>			
Comparison to I-CAM			
Compared to I-CAM	Findings compared with I-CAM		
<p style="text-align: center;">No.</p> <p style="text-align: center;">Investigation was not conducted. Incident prior to site I-CAM use.</p>	<p>_____</p>		

Incident 9:

Missing Alignment when Reversing Haul Truck to Shovel for loading

Critical Decision Method Summary			
Short Description from CDM	Main CDM Findings		
<p>This interview was regarding the general issues with alignment of the haul truck when backing into a shovel.</p> <p>The driver had not been involved in an incident, such as a collision with the bucket of a shovel.</p> <p>However, this is known to happen and the interviewee (a driver) was asked to describe in detail how this task is typically achieved.</p>	<p>The driver used a number of 'tricks' and cues when reversing. This included using just the left mirror, past tracks of haul trucks, horn or radio from the shovel operator to correct positioning.</p> <p>If the first truck to reverse to a particular position of the shovel lines up poorly there is a tendency for future drivers to use their tracks as a guide and repeat the mistake.</p> <p>The reversing camera is not very useful in lining up correctly but may help the driver pick up any rocks dropped by previous drivers.</p> <p>Glare from the sun in the side mirror, causing the driver to lose vision of the shovel for a short time, was thought to be the most common cause of lining up incorrectly.</p>		
Decision Representation and Design Suggestions			
Major Decision	Jump Code	Jump Icon	Suggested Design Interventions
<p>Decision to follow the 'failed' repeat paths of the driver was determined to be the most likely cause of lining up incorrectly.</p>	2-8		<p>Insert down-lights on shovels that indicate the zone, visible during the day and night, where truck should not park.</p> <p>This offers guidance to the operator that can correct previous incorrect paths made by other trucks.</p>
	Rationale		
<p>In a situation where this failure occurs the decision jumps straight from recognition of the previous tracks to following them without any evaluation of other options or the plan.</p>			
Comparison to I-CAM			
Compared to I-CAM	Findings compared with I-CAM		
<p>No. Not a specific incident.</p>	<p>_____</p>		

3.4 Discussion

The key findings of the research can be condensed into five discussion points.

3.4.1 Mining equipment incidents have complex causes

The CDM revealed many of the incidents related to mining equipment to be complex in nature involving the alignment of a number of events and the failure of numerous barriers of defence, commonly triggered by local atypical conditions. This aligns well with the James Reason model of the dynamics of organisational accident causation (Reason, 1990; Reason 1997) and supports the view that CDM could be a valuable tool to add to incident investigation. For example, in the above-reported incident where a bulldozer struck a grader, the immediate causes of unsafe acts involved the parking of the grader and loss of situational awareness by the bulldozer operator. However, upstream the local workplace factor of the design of traffic flow on site and the organisational factor of production pressure made the unsafe acts more likely to result in an incident.

3.4.2 CDM and the Decision Ladder increases in value with incident complexity

In general, the CDM interview process was able to establish a good understanding of the incident in most applications. In all situations CDM was able to establish a narrative of an incident. In each of these narratives there did appear to be a key decision or decisions made by human operators that were central to the eventual outcome. From this information, the Decision Ladder was able to be used to represent the decisions which aided the generation of seemingly appropriate design suggestions. In complex situations, the interview was successful not only in establishing the story of what happened, but also the critical decisions made and the operator's sense making related to these decisions. For example, the incident where a haul truck lost control whilst descending a ramp at first appeared to be a simple case of excessive speed for the conditions. However, further probing in the CDM found the decisions were significantly more complex, such as the complex team decision on judging when wet weather makes conditions too dangerous. Even the driver's choice of speed descending the ramp used significant environmental cues.

With less complex events, involving simpler decisions the first two stages of the CDM were helpful in establishing the circumstances surrounding the incident. However, if the decisions made were relatively straightforward using obvious environmental cues then the ‘deepening’ and ‘what if’ probes did not add significantly to the understanding of the event. From this information, the Decision Ladder was able to be used to represent the decisions which aided the generation of seemingly appropriate design suggestions. For example, the latter stages of CDM for the fire in the digger example (#7 in the results list) did not gain significant information because the cue of smoke and the action of pressing the fire suppression system was not a complex decision.

However, the Decision Ladder does have a limit to the representation of complex decisions. In this instance the decisions were able to be represented on single Decision Ladders. However, this may not be the case for more complex scenarios, especially those involving multiple decision makers and sequential decisions. In these cases, however, the use of a series of Decision Ladders could offer a solution. For example, Higgins (2003) found that in production controlled manufacturing, which has very tight timeframes and complex inter-related decisions, a series of ladders was required because a discovery in one decision triggered a connection to the ‘alert’ stage in another. This is depicted in Figure 3.12. As the introduction of new techniques and technologies in mining is likely to make systems more tightly coupled and complex, it is recommended that any future application of the Decision Ladder be designed in such a way that multiple Decision Ladders can be used.

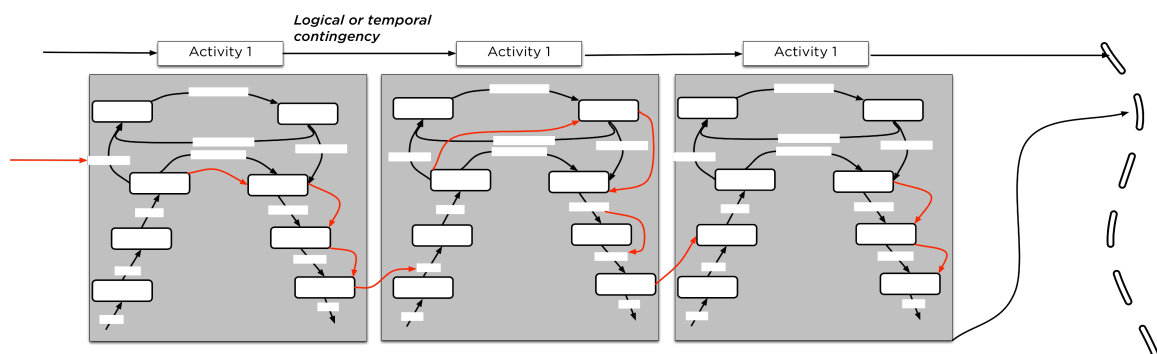


Figure 3.12: A sequence of Decision Ladders in a complex environment (Adapted from Higgins, 2003)

3.4.3 CDM uncovers important details not in site investigation reports

Upon reviewing the incidents it was evident that the CDM interviews identified information not contained in the I-CAM report. For example, in the incident where an overhead chute was impacted by a haul truck with the tray in the upright position (#4 in the results list), large colourful balls on wires – locally known as ‘idiot balls’ – were set below the height of the chute in the surrounding area. These serve as height indicators for drivers, similar to chains on low bridges or entrances to suburban car parks. They would have usually been contacted, prior to the chute, if a tray was in the upright position. However, a designated park up position for the haul truck was located past these balls. In this park up location, the operator raised the tray for a maintenance task and either forgot to lower it or did not notice that it had failed to lower before driving towards the reject bin. The location of the park-up bay and the idiot balls were not included in the incident investigation report.

In another example, the I-CAM report of the incident involving a road grader and a bulldozer (#6 in the results list) found that breaching procedures and not establishing radio contact between operators was the primary ‘*cause*’ of the accident. Therefore, a reminder to operators to follow procedures about radio contact was the sole action taken to prevent a repeat collision. However, the CDM identified that the background noise of the bulldozer and the hearing protection worn by the operator meant that it was likely that the operator could not hear the supplied radio and positive radio contact would not be established in this situation if repeated. Therefore, the provisional conclusion is that using the CDM method could assist in data gathering and building a rich incident narrative for I-CAM or similar investigation processes.

3.4.4 Site culture and hindsight need to be managed

During a number of interviews, it appeared that the site culture affected the interviewee’s perspective of the incidents. Specifically, the interviewees generally appeared reluctant to consider the influence of a system and more likely to blame the actions of people, including their own. They were often heard to use phrases like ‘I should have’ or ‘he should have’ and drift into generalisations about what was required by a specified procedure.

In one case, the participant noted that he and another employee shared the blame for a collision by not establishing positive radio contact when, in fact, it is likely that the radio system was unusable in the situation. This reflects Dekker's 'Bad Apple Theory' of human error where failures are introduced into a system due to unreliable persons and corrected by tightening procedures (Dekker, 2006). Therefore, occasionally it was necessary to prompt participants to investigate alternatives rather than using phrases like 'that would never happen'. This was especially so when investigations had already been undertaken and the findings had been widely disseminated.

3.4.5 Jumps in Decision Ladder revealed decisions were naturalistic

Jumps in the Decision Ladder occurred at levels that Rasmussen would describe as skill or rule-based (Rasmussen, 1986). Whilst this is only a sample of decisions, it does give some indication that explicit and simultaneous consideration of multiple options is probably uncommon for equipment operators. Rather, as would have been expected, operators appear to be making decisions in ways that are more congruous with naturalistic models. In the absence of other evidence, mobile equipment designers should, in general, avoid interventions that are time-consuming and require comparing multiple options in favour of those that improve the accuracy of heuristic jumps. The design ladder was able to display a decision path that is clearly explainable to managers. Therefore, it might be an effective tool in moving from a mindset of operator blame to design solutions that support naturalistic decisions.

However, whilst the Decision Ladder appeared a useful way to represent these decisions in a way that aided the selection of effective design solutions it would benefit from validation in mining. The current representations are only based on an interpretation by one researcher. The reliability of the ladders between users must therefore be verified. Additionally, whilst the ladder has been found to reliably lead to improved designs in other domains, the design recommendations described above remain unimplemented. Therefore, taking the design recommendations through to full concepts and implementation would be necessary to allow verification that the method can lead to improved designs.

3.5 Conclusions and Recommendations

3.5.1 Overall Value

The use of the CDM technique in the analysis of mining equipment incidents has shown that the knowledge elicited can provide a rich, operator-centred narrative. Also, it can provide valuable 'extra' information compared to the incident analysis methods currently in use (e.g. I-CAM). By focusing on the key decision points for operators, and unpicking the cues, information, goals, prior experience and related probes, the research was able to obtain a much deeper description of the incident events than the standard narratives used in much of the minerals industry today. Additionally, Decision Ladders can help represent the decisions and identify where redesigns could be of value.

3.5.2 Recommendations for Method Development

The use of CDM and Decision Ladders in mining could be beneficial to understand and document a wide variety of decisions. However, to date, it has largely been seen as a tool to be used by professionals. If their usefulness is to be tested in any widespread sense, then they must be packaged together as a single tool which could be more easily used with limited training. It is recommended that any packaging of the two methods into a single tool should include altering the language, especially of the Decision Ladder. Furthermore, it is recommended that the Decision Ladder be included in the interview with the participant directly involved in recording the decision path and making any design suggestions. Likewise, suggestions from other authors include attaching elements of the Decision Ladder to locations/objects/artefacts with the system (Jenkins, Stanton et al., 2010). This can be simply achieved by adding notes on each process of the ladder.

More widespread application could ultimately uncover common themes in critical decisions in mining. Such common themes have been used to successfully categorise event specific findings in healthcare after widespread application of CDM (Patterson, Render et al, 2002). The themes may be able to be matched with appropriate control suggestions. However, this would require widespread application of CDM in mining before enough reliable information is gained.

3.5.3 Recommendations for further research

Overall, by focusing on decision making in real mining environments, it is contended that this research successfully modified and applied the CDM technique to this domain. Once a toolkit has been established to allow efficient and consistent application, further work to now integrate it into mining incident investigation processes is strongly recommended. Additionally, the potential to apply CDM and the Decision Ladder proactively is an attractive topic for future research. Work with an underground gold mine was completed to test the technique's use when introducing a proximity detection system. This will be explored in the next Chapter.

Chapter 4

Evaluating the Effectiveness of an Underground Vehicle Proximity Detection System to Designed to Prevent Collisions

Abstract

Proximity detection technology is increasingly being employed in mining equipment in an attempt to prevent collisions. Such proximity detection systems rely on operator decision-making and action. To improve system usability, acceptance and effectiveness, a proximity detection device installed at an Australian underground gold mine was evaluated, redesigned and deployed using a range of human factors methods. The results of the evaluation of the proximity detection system identified deficiencies with the usability of the interface and limitations with the overall effectiveness of the system to help prevent collisions. An investigation of a subsequent collision at the mine site verified many of these observed issues. Interface redesign recommendations were made, and a new system was consequently developed and deployed. The subsequent change in operator acceptance after the implementation of the new interface was positive. It was concluded that the application of human factors methods can lead to positive changes to the design of proximity detection systems and, more broadly, to develop effective mining vehicle technologies from a user-centred perspective.

4.1 Introduction

4.1.1 Equipment Visibility and Injuries

Restricted operator vision from mobile mining equipment has been noted as an unresolved issue for safety in surface and underground operations (Bhattacherya, Dunn et al., 2006; Ruff, Coleman et al., 2011; Sammarco, Gallagher et al., 2012). The issue is most serious in underground environments where the requirement for

equipment to fit in small spaces severely restricts lines of sight from operating positions (Godwin, Eger et al., 2007). In this environment there is often less than one metre clearance between the vehicle, on both sides, and the walls (Simpson, Horberry et al., 2009). There are often situations where it is necessary for the operator to use the roof and walls, rather than the ground or road, as a guide. For example, Boocock and Weyman (1994) found that drivers of Load-Haul-Dump (LHD) vehicles have their vision restricted so much that they steer by looking along the near side of the equipment, concentrating on keeping the front corner as close to the wall. To make matters worse, pedestrians are often working in close proximity to the mobile equipment (Ruff, Coleman et al., 2011). Figure 4.1 shows a visibility assessment of an LHD.

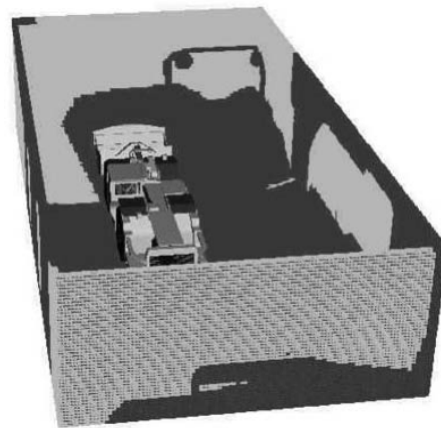


Figure 4.1: Visibility from an LHD. Black marks no operator line-of-sight (from Eger, Godwin et al. 2010)

The combination of these factors makes the interaction between mobile mining equipment and other equipment or persons intrinsically dangerous and collisions at underground mines have been noted to be a prevalent cause of serious injury or fatality (Eger, Salmoni et al., 2004; Burgess-Limerick, 2011). For example, recent Australian data suggest that approximately 35% of mining fatalities are due to vehicle interactions (Bell, 2009). Burgess-Limerick identified 41 fatalities occurring between 2000 and 2011 from collisions in underground coal mines operating in the U.S.A. (Burgess-Limerick, 2011).

4.1.2 Improving Line of Sight to Prevent Collisions

One obvious solution to the issue of limited visibility is to improve direct lines of sight from the driver's cabin. This could be paired with improving environmental impediments to visibility. On equipment currently in operation, this is unlikely to be possible. However, on new designs visibility can often be improved. For example one study found that a relatively simple human simulation software could be used to identify various design modifications to improve visibility on an underground Load-Haul-Dump vehicle (Godwin, Eger et al., 2008). Design modifications included as thinning light posts, lowering mudguards and adding windows. Some of these can be seen in Figure 4.2.

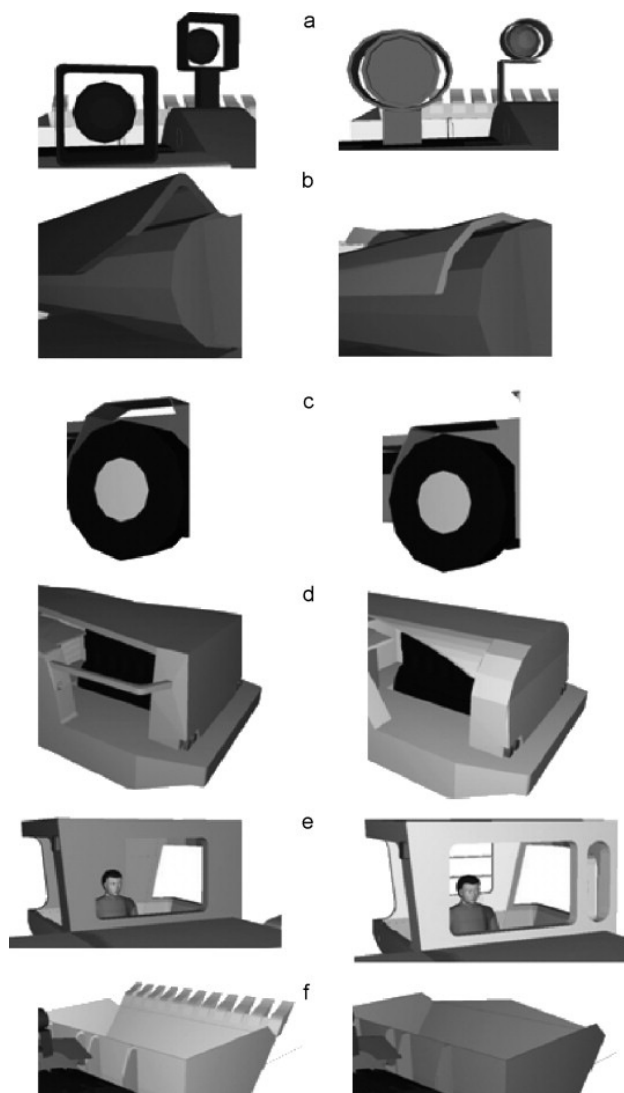


Figure 4.2: Design modification to improve visibility that note minimal improvement (from Godwin, Eger et al. 2008)

However, there are competing incentives in design which can limit visibility. This especially includes ensuring the cabin provides an operator with appropriate protection during equipment rollover and maximising load and haul capacity (Tyson, 1997). Additionally, underground mines still have restrictions on space and environmental limitations on visibility such tunnel walls. Therefore, even on new designs, vision from the operator's position will remain limited to some degree. In fact, in the study by Godwin, Eger et al cited above, the design modifications on new equipment did not improve visibility as substantially as they anticipated and they recommended that other safety strategies be concurrently pursued (Godwin, Eger et al., 2008).

4.1.3 Technological Support to Overcome Line of Sight Restrictions

Various technological aids to reduce collision risk have been trialled. The ultimate aim of these technologies is to prevent vehicles colliding with other vehicles, persons and infrastructure. They aim to assist the driver determine the location of equipment, people, or other obstacles in the surrounding environment and supplement other information sources such as radio communication, mirrors and direct line of sight. The most widely implemented aids are cameras that display blind spots of the vehicle to the driver via an in-cab display (Godwin and Eger, 2009). More recently, proximity detection, collision detection and collision avoidance systems have been deployed in mobile mining equipment such as haul trucks, trains and light vehicles (Horberry, Burgess-Limerick et al. 2010). These systems draw on a variety of technologies, which have been implemented to varying degrees, including radar, radio frequency tags, ultrasonic sensors, laser detection and GPS (Ruff, Coleman et al., 2011).

The common defining feature of these systems is that they all detect the presence of defined objects within an area around the equipment. Objects can be other pieces of equipment, defined pieces of infrastructure or even individual persons. However, a variety of actions post detection are possible, from leaving total responsibility for taking action to the equipment operator, to completely automated vehicle response. A graphical representation of the spectrum for the locus of controls of technology, adapted from Van der Laan et al (1997), is shown in Figure 4.3.

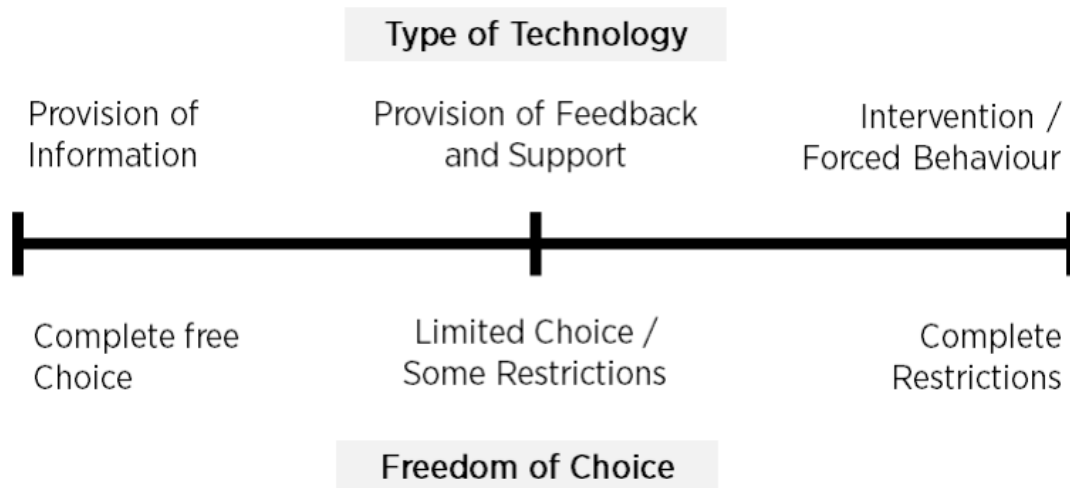


Figure 4.3: Locus of control spectrum of in-vehicle systems such as proximity detection (adapted from Van der Laan, 1997).

The technologies which automate actions based on detection either partially or fully restrict the choice of the operator. They are referred to as Collision Avoidance Technology (CAT) technologies and would fall to the right of the centre on the locus of control. The most common automated action is automatic machine braking or shut down. There are also technologies which simply provide information to operators, such as warning lights/alarms, and give them complete choice of the appropriate course of action. These are referred to as Proximity Detection Technology (PDT) technologies and are represented on the left on the locus of control. Some systems fall in the middle such as those that assess and communicate collision potential and those that suggest or restrict some actions. In mining, proximity detection technology is vastly more researched, available and implemented than collision avoidance technologies.

Other technologies to prevent collisions have been trialled. For example a lighting system which indicates vehicle movements to pedestrians has been found to improve the speed at which people detect vehicle movement, with the intention of increasing the time to take evasive action if necessary (Sammarco, Gallagher et al., 2012). However, the research and development effort to avoid collisions in mining has recently been extremely focused on proximity detection and collision avoidance systems. Its use is being pursued, and even compelled, in a number of jurisdictions (Horberry, Burgess-Limerick et al., 2011).

4.1.4 Relationship between Technology and Domain of Use

There are a variety of scenarios in mining in which proximity detection may be employed. This includes low speed vehicles operating underground, through to high speed driving on public surface roads. Therefore, it seems unlikely that a specific system, or for that matter a specific technology, will be suitable for all scenarios (Horberry, Burgess-Limerick et al., 2011).

In mining, collision detection and proximity warning systems cover a wide variety of technologies. However, each differs in where, when and how they can be used with the primary split between surface and underground operations. Despite huge differences in the equipment design, the operating environment technology developed for road transport can often be adapted for surface mining, including aspects of the human machine interface. This includes radar, Wi-Fi, camera, Radio Frequency Identification (RFID), GPS or Ultrasonic systems. However, in underground mining many sensor types used in road transport will not work and the operating environment is so different that human machine interface styles may not be applicable. Promising technology for underground proximity detection includes low frequency magnetic field markers and RFID.

4.1.5 Previous Research into Proximity Detection

Many proximity detection systems are currently subject to intensive research and development work by major equipment manufacturers, smaller enterprises, research institutes and mining companies. Overall, the current research has largely been from a technology-centred perspective, focused on ensuring appropriate sensitivity, accuracy and reliability to work in a specific environment. It also focuses on whether the systems can reliably detect selected objects in defined locations and transmit this detection to the driver. This appears to be the limit of published research on various proximity detection technologies such as RFID (Kloos, Guivant and Nebot, 2005), electromagnetic field generation (Jobes, Carr et al., 2011; Li, Carr et al., 2012) and radar (Ruff, 2001). There are some noted issues with the reliability of these technologies, especially their susceptibility to false positives suitability to environments (Horberry, Burgess-Limerick et al., 2011). However, broadly speaking, it does appear that proximity detection systems can now reliably detect and transmit information to the driver with considered implementation and maintenance.

4.1.6 Potential Issues with Proximity Detection

Unfortunately, the reliable automation of detecting and transmitting relevant information to the driver does not ensure that the system will be effective in aiding driver decision-making and, ultimately, reducing the risk of a collision. The most cursory analysis would note that proximity detection adds an in-cab interface, which has been noted to have the potential to distract rather than aid operators (Regan, Hallett et al., 2011). More broadly, proximity detection is an attempt at partial automation which often makes systems more complex and difficult to predict, especially where human behaviour is important. Despite this, designers are known to frequently fail to foresee or underestimate adaptations people will make with the introduction of automation. This is best encapsulated in the landmark paper *Humans and Automation; Use, Misuse, Disuse & Abuse* by Parasuraman et al which describes various ways that human adaptations can undermine or even reverse the benefits of automation on safety and efficiency (Parasuraman and Riley, 1997). Misuse refers to over-reliance, disuse to neglect or under-utilisation and abuse to automation of complex functions in a simplistic manner. All are possible downsides from the introduction of proximity detection.

Perhaps the most serious of the above negative consequences is misuse, which implies that the display of vehicle positions to drivers could result in behavioural adaptation to engage in riskier behaviours. This negative adaptation is termed 'risk compensation' (Hedlund, 2000). It has been documented to occur in various industries where automation is more advanced than mining, such as aviation, road transport and process control (Summala, 1996; Itoh, Sakami et al., 2000; Hartman, Dabipi et al., 2012). For example, the introduction of anti-lock braking has reported to have been met with driver adaptations to braking later (Evans, 1999) which could explain the difficulty in finding a correlation with a reduction in traffic accidents (Cummings and Grossman, 2007). There are even some documented cases of the introduction of proximity detection technology leading to unwanted adaptations. For example, the adaptation to over-reliance on a GPS shipping technology to monitor position caused a cruise ship to run aground when it silently failed (Lützhöft and Dekker, 2002).

This possibility of unwanted adaptation is especially likely where the automation occurs during co-operative work which relies on the exchange of information. Co-operative systems are usually seen in continually changing environments and respond to failures through self-adjustment and self-regulation (De Keyser, 1997). Loading and hauling in mine sites, where the routes, roads, environmental conditions and tasks are constantly fluctuating and drivers are continually communicating via t-way radio, can be considered a cooperative system. Increasing the level of automation in mining vehicle operation may not be the answer to collision prevention as there is possibility of over-reliance (Itoh, Sakami et al., 2000). Proximity Detection will succeed if it aids co-operation without other unwanted adaptations, but it will fail if it reduces co-operation or is associated with negative adaptations.

4.1.7 Research Gaps with Proximity Detection

Research into the human element considerations is necessary to determine the optimal presentation of proximity information to improve safety, or even if improving safety is achievable with a system using this technology. Unfortunately, in contrast to the technological side of proximity detection, there has been extremely limited research into human element considerations. There appears to have been an assumption in the mining industry that proximity detection systems will improve safety. However, this is not the case and it is simply not known if proximity detection information, once transmitted to the operator, can be appropriately interpreted in a timely manner to prevent collisions.

The most obvious area lacking research is the ability of human machine interface of the proximity detection system to optimally deliver information detected by the system so that it is correctly interpreted by the driver. As with road vehicles, a variety of interface types are possible for this technology, including warning lights/alarms through to automatic machine shut down when a likely collision is detected. No single interface type fits all application areas in mining, so a careful understanding of the differing user requirements, analysis of the different tasks and user-centred evaluation of prototype technologies is required (Horberry, Larsson et al., 2004). Furthermore, no single interface is applicable to all mining environments. Each context demands a careful, user-centred understanding in order to effectively implement the technology (Horberry, Larsson et al., 2004). Contextually appropriate

interface design will heavily affect the eventual effectiveness of proximity detection systems in preventing accidents (Sheridan, 2002).

But even more broadly than the interface, it is worth considering the context of potential collisions to determine where proximity detection could intervene and avoid collisions. Proximity detection systems can only be considered a low level on the hierarchy of control as they only offer warnings that the operator has to interpret expediently and correctly before any appropriate action can be taken. Therefore, it is possible that proximity detection would be limited in the effectiveness. Burgess-Limerick (2011) provides some evidence that simply providing information of vehicle location to drivers may not prevent collisions in underground mining. A review was undertaken of accident reports describing fatalities occurring due to collisions at underground coal mines in the U.S.A. in the ten years up to 2011. Of the 41 fatalities reviewed, in 56% of cases, the operator of the equipment was either aware of the location of the person who was killed, or the operator was the person killed. It was concluded that a technology that merely detects the presence of vehicles and persons is unlikely to be adequate in many cases.

As collision prevention is the ultimate aim, ideally research would take a holistic approach and consider how proximity detection works in concert with other risk controls. This will allow proximity detection systems to be effective in cases where they can assist, whilst highlighting the circumstances where proximity detection would be unlikely to or cannot provide adequate risk control.

4.1.8 Practical Considerations for Implementation

As proximity detection systems represent a change to existing mining practices, a number of practical considerations cannot be overlooked. Primarily, the technology should address a previously identified issue in a cost-effective manner without requiring extensive retrofitting to vehicles already in operation and extensive technological support to keep the system robust. It should be integrated with other equipment so that any information is a reliable reflection of the environment and intuitive enough to use during the complex operation of mobile mining equipment.

Finally, and perhaps most importantly, proximity detection must be accepted by operators. In order to be reach its potential, proximity detection technology not only has to useful but also satisfying to use (Lynas and Horberry, 2011). Otherwise the technology will not be accepted and instead used in a manner not intended, disabled or even sabotaged. This issue has been a noted risk in other vehicle automation systems (Horberry, Larsson et al., 2004). There is some evidence of it in mining automation. For example, a state of the art man-tracking system in a German underground coal mine designed to manage proximity to various hazards failed because the staff suspected an ulterior motive leading to sabotage (Macfarlane, 2001). It is also likely that operator acceptance of a technology is indicative of its value. The underlying assumption is that, because the operators are the experts, their acceptance is generally related to whether the technology aids them in driving. Operators will not sabotage technology which they feel is useful (Horberry, Larsson et al., 2004). Therefore, careful consideration of involving the end-users in at least the implementation and, ideally, the design of proximity detection systems will lead to the maximum chance of effectiveness.

4.2 Research Site

4.2.1 Description of the mine site and proximity/detection system

The study site was an underground gold mine in Queensland where a prototype proximity detection system was in use. A variety of mobile mining equipment were operated underground, including loaders/shovels (to load the ore onto a vehicle for removal), haul trucks (to remove the ore to the surface) and light vehicles (for a variety of maintenance and technical purposes, including setting charges for rock blasting). Figure 4.4 shows some haul trucks and loader used to load these trucks.



Figure 4.4: Examples of vehicles used underground: a) haul trucks, b) loader

4.2.2 Description of proximity detection system at the site

The mine installed a RFID-based system primarily to improve the monitoring of production. Tablet PCs attached to tag readers were installed in haul truck and loaders at the mine. The tablets automatically read a number of tags around the mine to assist in tracking production including cycle times, delays, dump position and load weight consistency. However, though the tracking of production was the primary driver for the installation of the system, the mine management saw the opportunity to add a proximity detection system with the aim of reducing the risk of collision between vehicles. The following are some of the notable features of the proximity detection system:

- When another vehicle is detected, the code for that vehicle is displayed on the screen. Part of the code indicates the type of vehicle (e.g. LV403. TORO141). Codes are displayed in a list with the most recent unacknowledged vehicles at the bottom.
- Six vehicles can be displayed on the screen. If the number of vehicles detected is greater than six these will be displayed on subsequent screens, which can be accessed with a scrolling feature.
- A timer starts next to the code, following the initial detection of the vehicle, indicating how long it has been continually detected. The timer will continue until the vehicle is no longer detected.
- A sound is emitted from the PC and the code flashes upon initial detection (the colour varies on the colour scheme used). The sound tone is alterable by the operator, and can be significantly turned down. It was reported by an operator that with hearing protection and the volume set low, the sound could no longer be heard.
- When the presence of the vehicle is acknowledged, by the operator touching the code on the screen, the sound ceases and the vehicle code changes colour and stops flashing. When the vehicle is no longer detected it is removed from the screen whether or not the driver has acknowledged its presence by touching the screen.

Figure 4.5 shows an example of proximity detection screen in a vehicle cab (the screen is shown in upper left hand side) and Figure 4.6 shows an example of the system interface.



		15:38:14 AUG 7
4	VEHICLES DETECTED	
	LV01	101 00:25:53
	Bogger 1700	326 00:01:17
	LV06	106 00:00:57
	TORO 141	341 00:00:47
PAGE 1 OF 1		
	1600 BOGGER 214 -> SURFACE ORE	
	HAUL EMPTY	
	STANDBY	
	SCR N SAVER	

Figure 4.5: Screen position in cab Figure 4.6: The first system interface

The following are some of the developer-acknowledged limitations of the proximity detection system:

- No direction of the detected vehicles is given to the operator. In an underground environment it is unlikely that directional capacity will work with an RFID system other than 'forwards' or 'rear' with the use of two antennas.
- There is no set distance for when a vehicle will enter and exit detection. For example, the detection distance was thought to be much greater when on high ground on the surface than when underground. This was reported to be many hundreds of meters on the surface, down to less than 20 metres, or even missed detection, underground.
- The system only acknowledges the presence of a vehicle but not that it is necessarily dangerous or requires action. The driver must still interpret the necessary course of action based on this information and other features of the environment.

4.3 Research Objective

The general objective of the research was to determine whether human factors methods could predict (and help improve) the issues with the complex cognitive tasks associated with proximity warning systems in mobile mining equipment. This was achieved through a series of methods at the above site, some of which have been used in previous chapters (such as CDM). The more specific purpose of the research was to provide recommendations for future system development and, where possible, implement and evaluate these changes.

4.4 Methods

The research approached the issue from both a problem and a user-centred perspective, rather than from a technology-centred position. Therefore, a variety of methods were used to explore the issue which are described below. This took place in three distinct phases.

4.4.1 Research Phase 1: Investigation Methods

Investigation methods were used to holistically explore system risk controls and failure modes with the hope of recommending improvements. This included but was not limited to the proximity detection system and determined some recommended changes. The methods employed are listed below.

4.4.1.1 Exploration of System Constraints

At the onset of the research it was evident that the mine site was aware that detection distance may vary considerably depending on the scenario. However, it was unknown how much distance varied; equally, it was unknown what the effects of different variables such as underground road position were. A logical starting point was an exploration of the constraints and detection reliability of the system. Without this, it was difficult to determine if the system could effectively assist operator decision making in respect of other vehicles.

Detection distances at different locations at the mine (surface and underground) were analysed. Whilst underground, the truck was approached with a hand held RFID tag attached to an antenna (like those installed in light vehicles working underground), from different locations. The truck was also placed facing towards

(forwards) the tag or away from the tag (backwards). The measurements were recorded three times for each scenario, to determine variability and accuracy of the measurements. As the system used RFID, there were sections where the radio waves would need to bounce around corners. However, line of sight was possible on a long straight section of the mine. The different types of corners examined are depicted in Figure 4.7 below.

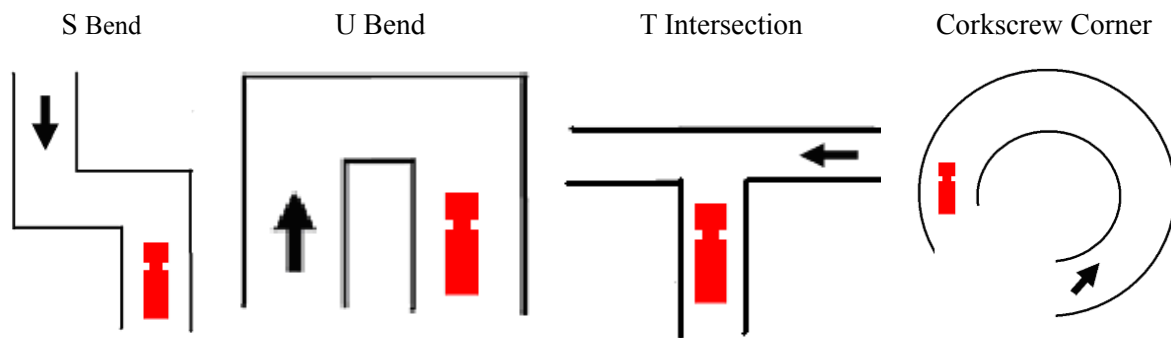


Figure 4.7: Different types of underground corners investigated

4.4.1.2 Ergonomic audit of the collision/proximity system interface

Two researchers with postgraduate qualifications in Ergonomics/Human factors reviewed the interface. The primary tool used (after suitable adaptation to the exact context of this research) was the TRL Safety Checklist for the Assessment of In-Vehicle Information Systems (Stevens, Board et al., 1999). Both experimenters separately viewed the interface in a haul truck at the mine and later compared their assessments to determine significant usability defects. The goal was to determine any generic user interface design errors.

4.4.1.3 Naturalistic field study

The small-scale naturalistic field study recorded operator behaviour whilst using the proximity detection system in a large mobile mining vehicle. In particular, two measures were recorded: a) filming the operator whilst driving the vehicle underground, and b) proximity data collected by the system. This second element included other vehicles detected and operator responses to acknowledge these vehicles to assess whether major changes in driving behaviour occurred after another vehicle had been detected. Data from one operator were recorded. Due to

this low number, the data collected here were used to verify and further explore driver reports about the use of the system that were obtained from the below-mentioned interviews.

4.4.1.4 Cognitive Tasks Analyses and Structured Interview Methods

Knowledge and experiences were elicited from operators involved in previous mobile equipment collisions or who used the current proximity detection system. This allowed a detailed user-centred perspective of equipment operation tasks and the current controls in place. Initially, it was planned to use the Critical Decision Method (CDM) to elicit knowledge about vehicle incidents and near misses, on the basis that these represented 'tough cases' which has previously been found to be an efficient way of eliciting knowledge from experts (Crandall, Klein et al., 2006; Klein, 2008). However, the interviewees were unable or unwilling to recall real incidents to analyse (partly because of the newness of the system).

Instead, the operators were asked to consider where they felt the more complex areas of road and vehicle interaction were in a mine and construct a fictional, but possible, scenario of a collision occurring. This included the position of the vehicles in the mine and the other barriers that would need to fail in order for proximity detection to be useful. Though not real scenarios, it did show a logical path to failure, and helped determine what features a proximity detection would need for it to be effective. These features could then be compared to the current prototype RFID proximity detection system in place.

Eight operators were interviewed by two experimenters. In every interview, the operator was able to construct plausible scenarios where a collision could occur and a proximity detection system could be useful should other controls fail. This included scenarios in the underground, on surface haul roads and around workshop areas. This method was then repeated in a group setting and applied to key operational scenarios encountered at a mine.

4.4.2 Phase 2: Accident Investigation

Serendipitously, after the above methods had been applied and were being analysed, a collision occurred between two vehicles at the mine. A load-haul-dump

(LHD) was waiting in the underground workshop for a service vehicle to arrive for refuelling. When the service vehicle arrived, upon seeing the loader in the service bay, it backed up the main decline to allow the loader to exit. Upon exiting the workshop, the LHD struck a light vehicle (LV) ascending the main decline. The loader bucket struck the bonnet of the vehicle causing equipment damage. No persons were injured, but there was the potential for fatal injury. All vehicle operators involved in the incident were interviewed using the Critical Decision Method (as described earlier in the thesis). Additionally, movements of the vehicles were reconstructed in-situ to assist in reviewing the incident. This involved placing a LV in the decline at approximately the impact point and approaching it with a LHD. Also, a LV was driven up the decline and down the decline past the Loader in the workshop to test proximity detection system. Full details of the incident investigation are shown in Appendix 1.

4.4.3 Phase 3: Evaluation of Modifications

Following the accident investigation, a number of changes were made to the proximity detection system. In order to gauge the success of the interface changes that were made, the equipment operators were surveyed. 18 of the 20 operators who worked at the mine completed the survey. The survey was conducted primarily to determine how accepting the drivers were of the initial system and, in comparison, the altered system. Drivers were also asked to rate the effectiveness of the system(s), the importance of other controls, and their opinions about further proposed changes.

4.4.3.1 Operator Ratings of Acceptance of the Proximity Detection System

An established method for measuring driver acceptance has been developed by Van der Laan et al. (1997). This technique was selected because it had been frequently applied in several different studies of measuring the acceptance of in-vehicle systems, including collision avoidance systems with auditory feedback in a variety of environments (Hoedemaeker and Brookhuis, 1998; Brookhuis and de Waard, 1999; Vlassenroot, Broekx et al., 2007). In these studies, it was found to be a good measure of both absolute acceptance and was sensitive enough to determine relative/comparative acceptance amongst groups or technology options.

Using this technique, a five-point rating scale was used for nine questions rating acceptance of the initial and altered interface of the proximity detection system. Drivers selected between five boxes placed between two opposing qualitative words. The position of the positive and negative words is sometimes reversed. The positive words are shown in bold italics in Table 4.1.

1	<i>Useful</i>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Useless
2	<i>Pleasant</i>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Unpleasant
3	Bad	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<i>Good</i>
4	<i>Nice</i>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Annoying
5	<i>Effective</i>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Superfluous
6	Irritating	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<i>Likeable</i>
7	<i>Assisting</i>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Worthless
8	Undesirable	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<i>Desirable</i>
9	<i>Raising Alertness</i>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Sleep Inducing

Table 4.1

Acceptance of technology ratings (based on Van der Laan et al, 1997)

The sum of all questions made up a score for 'acceptance'. Additionally, the odd numbered questions (i.e. 1, 3, 5, 9) are a rating of 'usefulness' and the even numbered questions (i.e. 2, 4, 6, 8) are a rating of 'satisfaction'. Drivers were all initially asked to make a rating of the current proximity detection system. Those drivers who were working at the mine with the previous system were also requested to make a rating of the previous system. In the scoring system for the scales determined by the Van der Laan, the middle box represented a score of 0, the boxes either side represented -1 to +1 and the outer boxes +2 or -2. However, in this case, Van der Laan's scoring system was adapted here to be positive numbers only (1- 5) to allow shape plotting on a radar graph. By joining up each of the ratings, an irregular polygon is formed and these types of radar graphs are particularly useful to visually communicating the overall change. This change does not alter the analysis in any other way. The original and adapted scoring can be seen in Table 4.2

Van der Laan's Score	-1	-2	0	+1	+2
	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Adapted Score	+1	+2	+3	+4	+5

Table 4.2
Acceptance of technology scoring scale

4.4.3.2 Relative Effectiveness of Proximity Detection to Other Risk Controls

As stated in the above section, the research considered not just the proximity detection system in isolation, but all the risk controls preventing collision. Through discussions with a Subject Matter Expert (the mine manager), a list of these controls that are relevant to the operator's decision making was compiled. It was given to the operators to rank in terms of its effectiveness. The reason for this was to determine the perceived effectiveness of all of the controls and potentially check the importance of proximity detection as compared to other collision prevention measures.

The following eight risk controls were presented to the operators:

1. Two Way Radio
2. Naming Locations Around the mine
3. Knowledge of mine roads/intersections
4. Forwards Direct vision out of your vehicle
5. Horns to communicate presence to others
6. Headlights of other vehicle approaching
7. Proximity Detection System
8. Reverse Camera and / or Rear Mirrors

They ranked each control on a 4 point scale of: Not – Somewhat – Quite - Very

The questions about the relative effectiveness of proximity detection relative to other risk controls were part of the survey about driver acceptance. So, 18 of the 20 operators who worked at the mine gave their options.

4.5 Results

4.5.1 Research Phase 1: Investigation Methods

4.5.1.1 Exploration of System Constraints

Results regarding detection are shown below. As seen in Figure 4.8, they show, for example, that backwards detection was less than forwards detection, and was non-existent around S or U bends backwards underground.

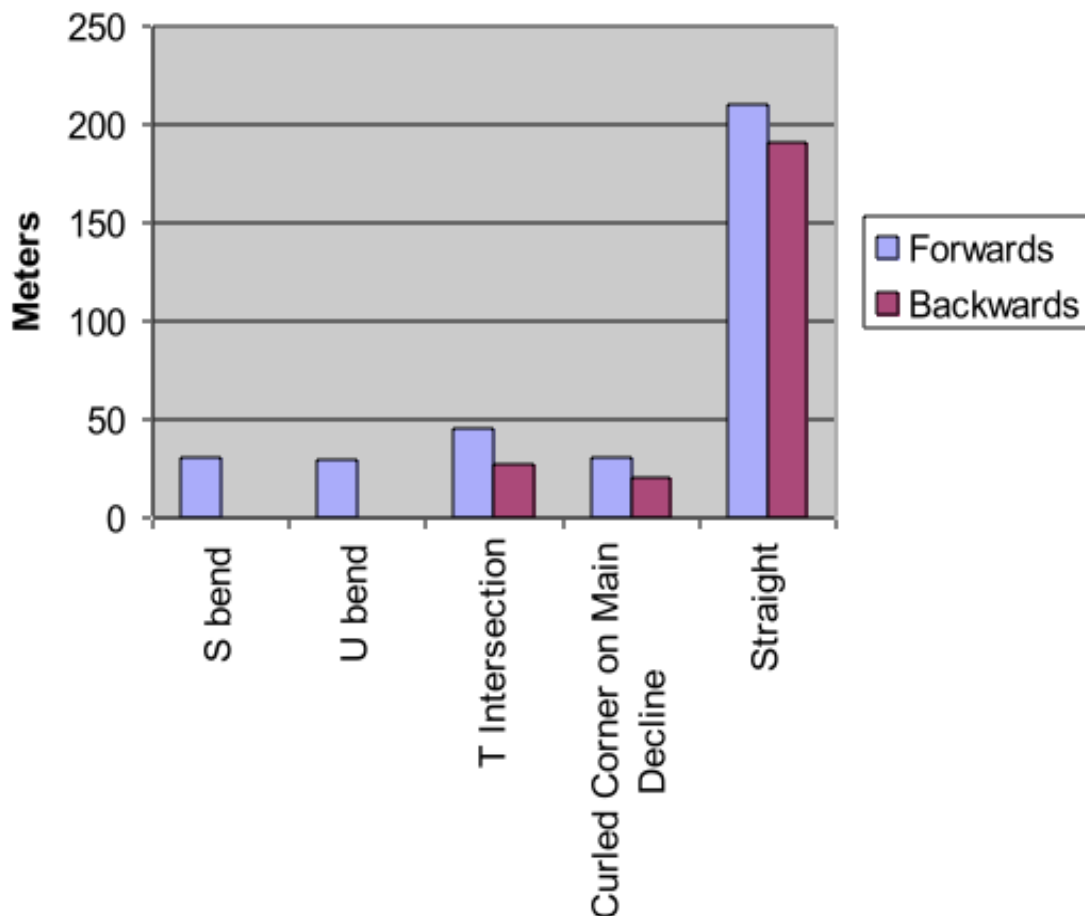


Figure 4.8: Detection distances at different locations underground and on the surface

Additionally, it was found that different equipment (eg different model RFID tags and longer connecting leads) significantly influenced detection distances. Finally, as hypothesised, detection distances were longer on the surface compared with underground.

4.5.1.2 Ergonomic audit of the collision/proximity system interface

The researchers independently applied a checklist developed by the Transport Research Laboratory to serve as a structured aid to assist the experts in the evaluation of In-vehicle information and communication systems. The checklist primarily looks at simple usability issues, such as menu structure, glare, reach and distraction. No significant usability issues were identified, but some of the more minor issues were:

- the potential to distract from driving when acknowledging multiple vehicle detections,
- auditory feedback being able to be reduced to where it can no longer be heard, and
- the possibility of glare making the screen difficult to read.

Of course, the audit was not detailed enough to conclude if the information given by interface would aid driver decision making, reducing the risk of collisions. However, some issues for further investigation were noted, such as the lack of distance and direction of vehicles, the variability in detection distances and the possibility of large numbers of detections at one time.

4.5.1.3 Naturalistic field study

The naturalistic field study showed that the driver used for the study never acknowledged the detected vehicles by touching the interface, but appeared to glance at the screen on detection indicating they have cognitively acknowledged the detection. All the equipment codes continued flashing on the screen until they could no longer be detected. In some cases this was for minutes, indicating a vehicle was following behind. The screen appeared very bright in a dark cab when the vehicle was underground, consistent with operator interview reports the screen can produce glare (see Figure 4.9). There was no notable change in driving behaviour on detection, though this would have been difficult to determine unless a non-routine situation occurred.



Figure 4.9

Vehicle cabin underground, showing proximity detection screen

4.5.1.4 Cognitive Tasks Analyses and Structured Interview Methods

The interview findings regarding operator opinions of the technology were broadly similar to many of the 'classic' human factors issues with automation and new technologies identified in other domains (Bainbridge, 1983; Sheridan, 2002). These include shorter term issues such as non-optimal interface/warning design, plus longer terms challenges such as technology acceptance, trust and skills fade. Additionally operators stated that there might be unanticipated side effects related to over-reliance on the technology.

The interviews were successfully able to determine scenarios where proximity detection, if effective, may prevent collisions. Each scenario was represented using Energy Trace and Barrier Analysis (ETBA) to qualitatively show how the moving mass of a truck (the energy) could avoid control. In all scenarios, additional controls that assist operator knowledge of the location of other vehicles were required to fail; most notably radio communication, where drivers are required to regularly 'call' their position and direction, and visual location of the vehicle, either directly or through a reverse angle camera mounted in the cab. The schematic images in Figure 4.10

show an example of where a proximity detection system may act as a control should other controls fail.

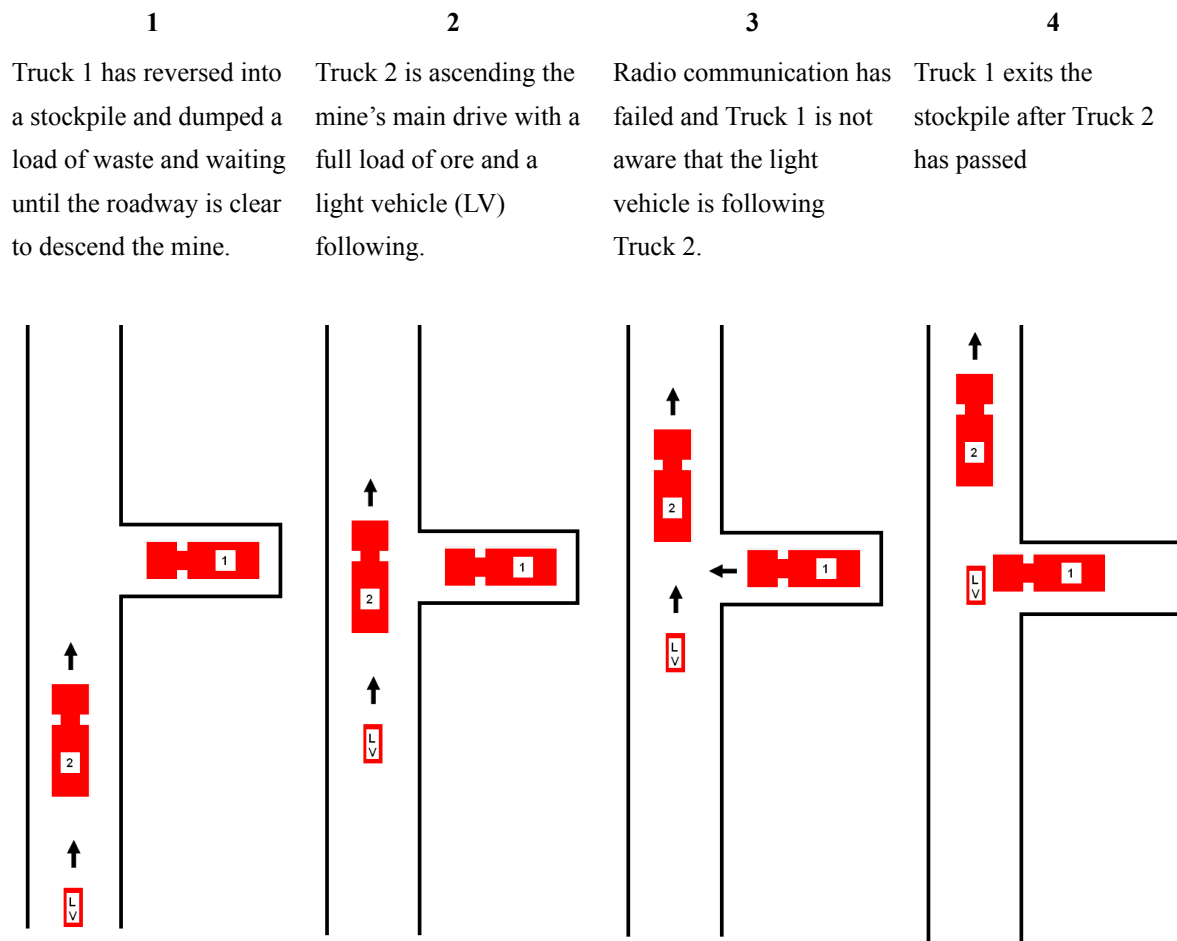


Figure 4.10 : Proximity detection system acting as a control where other controls fail

Overall, it was found that proximity detection normally acted as a valuable extra control, in addition to the others already utilised by drivers. However, several operators thought the system could reduce the effectiveness of other controls, especially radio contact, through over-reliance on the system. Furthermore, a number of failure modes were detected for the proximity detection system. All the controls that prevent collisions and their failure modes are included in Table 4.3.

Table 4.3: Failure Modes of Controls that Prevent Collisions

Control	Description	Failure modes
Radio	2 way radio between all light and heavy vehicles operating. When driving underground, operators are instructed to regularly call their location and direction.	<p>A driver has radio on a different channel.</p> <p>Radio 'dead spots'.</p> <p>Radio electrically fails.</p> <p>Radio calls of heavy volume, spacing out or blocking calls.</p> <p>Radio is not or infrequently used.</p> <p>Radio volume is turned very low or off.</p>
Location Signage/ Naming	The naming of locations throughout the mine either by names (eg. 'Haul Road', 'Workshop') or depth underground spray painted on mine wall (eg. '600').	<p>Location name hard to interpret</p> <p>Location can be easily confused with another location (eg. Similar name).</p> <p>Location is not named at all.</p> <p>Location name is large, making exact location non-specific.</p> <p>Location has multiple names, or colloquial name that could be confused or not known.</p>
Location Mental Model	The mental model drivers have of the mine allowing them interpreted their location and radio calls of others.	<p>Inexperienced drivers lack mental model</p> <p>Experienced driver over interpret a location to usual route, when unusual route is being taken.</p> <p>Complexity and frequency of calls makes it difficult to remember locations of all vehicles.</p>
Direct Vision	Driver of vehicles can directly see vehicles approaching out the vehicle window.	<p>Blind spots, particularly from heavy vehicle.</p> <p>Driver is looking in direction other than vehicle approaching</p> <p>Mud/Dust on windscreen</p> <p>Vehicle is hidden from direct sight by obstruction (eg. around corner.)</p>
Headlights	In the underground environment, seeing headlights approaching, especially around corners and intersections.	<p>Headlights are not on.</p> <p>Headlights on approaching vehicle are obscured by headlights of driver's vehicle.</p> <p>Backlit area prevents headlight being seen.</p> <p>Interaction is on surface in the daylight, where headlights do not assist.</p>
Roadway Design	Roadways designed to eliminate or minimise head on vehicle interaction	<p>Roadway is not wide enough to allow two vehicles to pass.</p> <p>Roadway does not physically separate vehicles, either by signs/markings or physically.</p>

Control	Description	Failure modes
Proximity Detection	RFID proximity detection system with readers in large vehicles and tags on all vehicles. Direction is not included. Distance is variable on location.	Driver not aware of detection and it not alerted by sound (eg. looking other direction)
		Driver misinterprets detection of a vehicle for an alternative in a different direction.
		Driver misinterprets detection direction (eg. that a vehicle is detected in front but interprets it to the rear.)
		Too many detections to interpret
		Detection is on subsequent screen (only 6 on home screen, and new ones added at rear).
		Detection does not occur in time
Horns	Driver uses horn to alert other vehicle and halt movement.	Horn cannot be heard (eg. engine noise.)
		Horn misinterpreted (eg source, meaning).
		Horn is used too late.
		Horn is not used
Evasive Action	Drivers notice a collision is about to occur and take evasive action driving actions.	Driver cannot take action in time.
		Driver does not have the available room to take action (eg. backed into stockpile).
		Driver takes evasive action, but then becomes blocked (eg. wall/ ditch/ embankment/ vehicle).

4.5.2 Phase 2: Accident Investigation

Many of the predicted/operator reported issues identified by the above-mentioned failure modes analysis of the controls were validated following a collision at the mine between a LHD and a LV. In general, the controls failed in a way that was predicted and no unpredicted failure modes occurred. The failure modes that occurred in this incident are italicised and shown in bold in the Table 4.4. Notably, 8 controls needed to fail with 12 distinct failure modes. Full details of the incident investigation and the distinct failure modes are shown in Appendix 1.

Table 4.4: Controls that failed in the Accident

Control	Failure modes
Radio	<i>A driver has radio on a different channel.</i>
	Radio 'dead spots'.
	Radio electrically fails.
	Radio calls of heavy volume, spacing out or blocking calls.
	<i>Radio is not or infrequently used.</i>
	Radio volume is turned very low or off.
Location Signage/ Naming	Location name hard to interpret
	Location can be easily confused with another location (eg. Similar name).
	Location is not named at all.
	Location name is large, making exact location non-specific.
	Location has multiple names, or colloquial name that could be confused or not known.
Location Mental Model	Inexperienced drivers lack mental model
	<i>Experienced driver over interpret a location to usual route, when unusual route is being taken.</i>
	Complexity and frequency of calls makes it difficult to remember locations of all vehicles.
Direct Vision	<i>Blind spots, particularly from heavy vehicle.</i>
	<i>Driver is looking in direction other than vehicle approaching</i>
	Mud/Dust on windscreen
	Vehicle is hidden from direct sight by obstruction (eg. around corner.)
Headlights	Headlights are not on.
	<i>Headlights on approaching vehicle are obscured by headlights of driver's vehicle.</i>
	<i>Backlit area prevents headlight being seen.</i>
	Interaction is on surface in the daylight, where headlights do not assist.
Roadway Design	<i>Roadway is not wide enough to allow two vehicles to pass.</i>
	Roadway does not physically separate vehicles, either by signs/markings or physically.

Table 4.4 Continued: Controls that failed in the Accident

Control	Failure modes
Proximity Detection	Driver not aware of detection and it not alerted by sound (eg. looking other direction)
	Driver misinterprets detection of a vehicle for an alternative in a different direction.
	Driver misinterprets detection direction
	Too many detections to interpret
	Detection is on subsequent screen (only 6 on home screen, and new ones added at rear).
	Detection does not occur in time
Horns	Horn cannot be heard (eg. engine noise.)
	Horn misinterpreted (eg source, meaning).
	Horn is used too late.
	Horn is not used
Evasive Action	Driver cannot take action in time.
	Driver does not have the available room to take action (eg. backed into stockpile).
	Driver takes evasive action, but then becomes blocked.

Perhaps the key finding here was therefore that many controls failed in the accident analysed here, and that one of these was the proximity detection system.

4.5.3 Phase 3: Evaluation of Modifications

4.5.3.1 Recommended Modifications

From the phases 1 and 2, a number of changes to the touch screen computer interface were suggested. The following changes were made to the system (see Figure 4.11):

1. Making the audio alarm a short sharp sound, rather than continuing until the computer interface was touched.
2. The detected vehicle flashes on the computer screen for a short period of time and then stops flashing, rather than ongoing flashing until the computer interface is touched.
3. Adding new vehicles to the top of the list on the computer screen, rather than to the bottom of the screen, where they were added previously.

In addition, the research recommended the following changes. In discussion with the technology manufacturer these were planned to be included in the next full proximity detection system upgrade:

4. Turning off the proximity detection system when vehicles are on the surface, due to reports of too many tag readings being registered on the computer interface to make the system useful.
5. Indicating if a vehicle is detected from the front or rear of the existing vehicle.

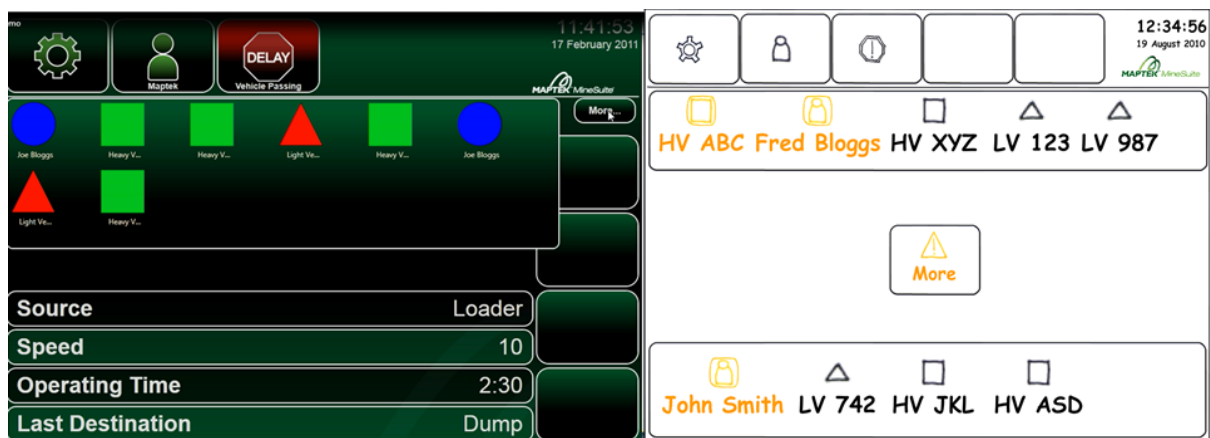


Figure 4.11: Revised proximity detection screens with and without direction.

4.5.3.2 Operator Ratings of Acceptance of the Proximity Detection System

Driver acceptance of the changes made to the proximity detection system was examined. Two polygons were plotted and layered to reveal acceptance of the drivers with the initial and revised proximity detection systems. The 1 to 9 around the polygon represents the questions asked of the drivers. A 'maximum', shown with a solid line, represents a score of 5 by all drivers on all measures. This shows how far the system is from the 'theoretical' maximum, though the capacity of the technology may well be lower. A 'positive negative line', shown with a dotted line, represents the average score of 3 on all measures.

In Figure 4.12, the acceptance of the first interface is shown in the lighter grey. The acceptance of the altered (new) interface is shown in darker grey. Parts of the

interface polygons below the 'positive negative line' represent a negative view of the interface.

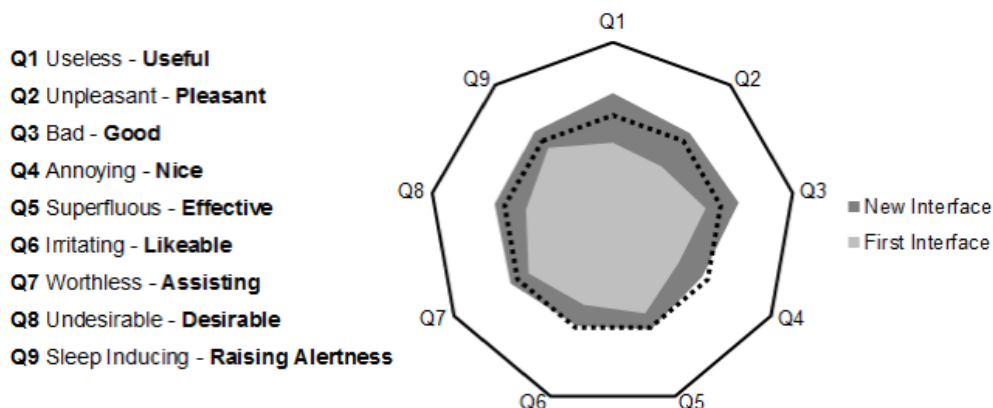


Figure 4.12: Operator acceptance ratings (original and revised interface)

The results show that before the small numbers of changes to the system were made drivers, on average, were not accepting the system, finding it useful or satisfying. After the system changes, all measures saw an increase. On all of the measures, except Q4 and Q6, the drivers gave overall positive ratings of the revised system. Both these measures are in the 'satisfying' portion of the survey. This indicates that, on average, the drivers have mildly positive 'acceptance' of the system, are mildly positive about its 'usefulness' and neither positive nor negative about 'satisfaction' with the system. As seen in Table 4.5, inferential statistics (t test) applied these results to and all reached margins of statistical significance.

Table 4.5: T-test results for operator acceptance

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
New Interface	3.62	3.28	3.50	2.83	3.06	2.94	3.22	3.28	3.33
First Interface	2.25	2.08	2.58	2.08	2.58	2.33	2.67	2.42	2.75
Significance	0.0003 6	0.0015	0.09	0.026	0.05	0.037	0.05	0.047	0.0295
Usefulness	0.051 (marginally significant)- ie the current interface is significantly more useful than the old one								
Satisfying	0.013 (statistically significant) - ie the current interface is significantly more satisfying than the old one								
Overall	0.0056 (statistically significant) ie the current interface is significantly more acceptable than the old one								

4.5.3.3 Relative Effectiveness of Proximity Detection to Other Risk Controls

The four point scoring system (of 'not', 'somewhat', 'quite' and 'very') was converted into a scale of 1-4 (with 4 therefore being a measure high relative effectiveness).

Figure 4.13 shows the results.

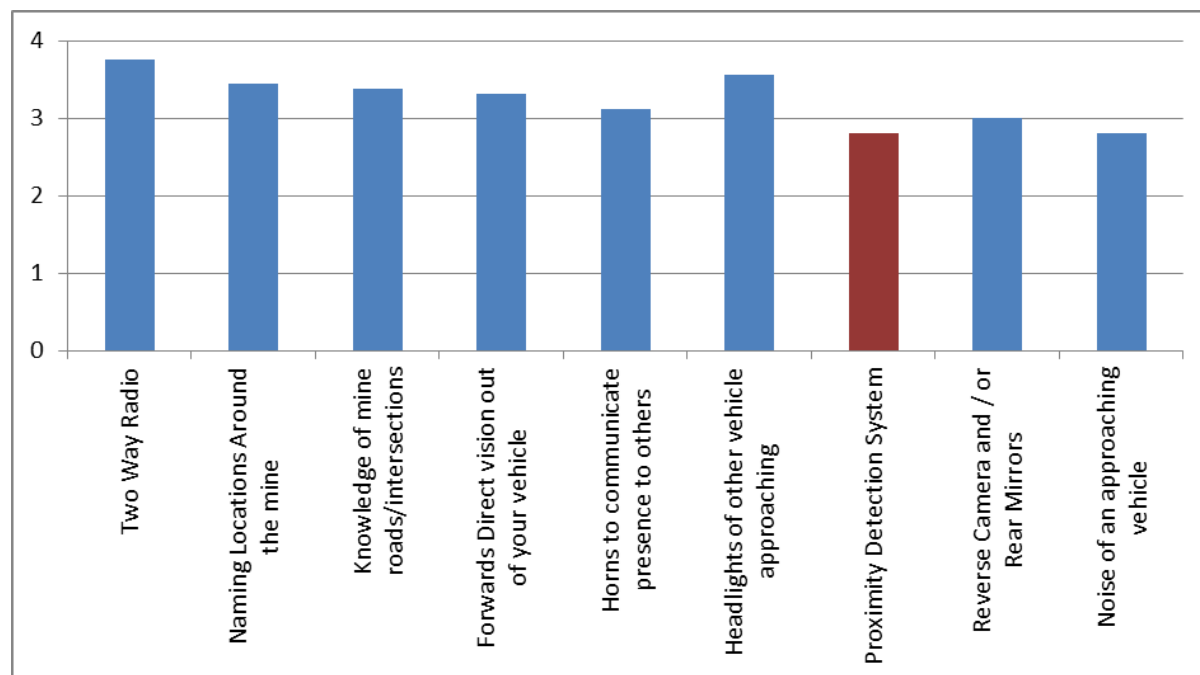


Figure 4.13: Relative effectiveness of proximity detection to other controls

The differences between the nine different controls were not statistically significant. In general, all controls were rated as relatively effective. With the proximity detection system, this is perhaps surprising as some resistance to change and negative opinions of new mining technologies has previously been reported (eg Lynas and Horberry, 2011). As such, a well-designed proximity detection system may be effective as part of a suite of controls.

4.6 Discussion and Recommendations

The multifaceted research approach with significant involvement of system end-users not only assisted in determining the effectiveness of the currently installed system but also redesigned and evaluated a revised system. The results of the evaluation of the initial proximity detection system identified deficiencies with the

usability of the interface and limitations with the overall effectiveness of the system to help prevent collisions. These included:

- varying detection distances underground (especially to the rear of the vehicle),
- poor interface design (potential to distract from driving when acknowledging multiple vehicle detections, and a driver never acknowledged the detected vehicles by touching the interface),
- operator perceived issues with trust, acceptance and skills fade, and
- how proximity detection can act as an extra control, and how this could fail (eg driver misinterprets detection of a vehicle for an alternative in a different direction).

The investigation of a collision at the mine site confirmed many of these observed issues and failure modes for controls. From this, interface redesign recommendations were made, and a new system was developed and deployed. This revised system was then tested for operator acceptance.

The results show that before the system changes drivers, on average, were not accepting of the device: finding it neither particularly useful nor satisfying. After the system changes, all measures saw a more positive rating. On 7 of the 9 measures with the revised interface, drivers gave overall positive ratings for the system. Both the two negative measures are in the 'satisfying' component of the Van Der Laan et al (1997) acceptance construct. This therefore indicates that drivers have mildly positive overall 'acceptance' of the revised system, are mildly positive about its 'usefulness' and are neither positive nor negative about its 'satisfaction'.

Due to the nature of this trial, it was not possible to counter-balance the *before* and *after* conditions. Consequently, the procedure might have been a source of bias – for example, due to the drivers 'expecting' improvements. Nonetheless, this possible criticism does not account for the nature of the mining industry, where the drivers were generally sceptical about both the technology and the research (so were in no

way inclined to give ratings simply to appease the researchers or the mine's management) (Simpson et al, 2009).

Acceptance of new technology is extremely important in subsequent technology utilisation. In isolated mine site environments, operators sometimes have the opportunity to choose to avoid using new technologies even when they are mandated. Therefore, if drivers did not accept the proximity detection technology then its potential to prevent accidents may never be realised. In field usage conditions, the original interface showed several negative behavioural responses, with some drivers admitted to turning down the sound and brightness of the computer screen, in order to avoid the system as much as possible. With improved acceptance of the new interface it is anticipated that the drivers will be much less likely to try and avoid using the system. The underlying assumption behind this is that, because the operators are the experts, their acceptance is generally related to whether the technology aids them in driving the heavy mining vehicles. As mine site accidents are extremely rare, testing the effectiveness of a proximity detection system in terms of incident rates is both difficult and, potentially, unethical. Therefore, it is recommended that carefully-used measures of technology acceptance are more widely used to provide a valuable intermediate measure.

In conclusion, well designed in-vehicle technologies, including collision/proximity detection, can help produce significant safety benefits in mining situations where off-road haulage is responsible for a significant number of fatalities (Groves, Kecojevic et al., 2007). Mining has the opportunity to learn from other domains such as road transport and aviation, and develop and implement technology from both a human-centred and an operational need perspective. Therefore, rather than being purely introduced because the technology is available, careful consideration must be given to how it will support the users' tasks, and how it will be integrated with other existing technologies & management systems. In fact, the methods should not be applied in order to maximise the effectiveness of a specific technology. Rather, human factors methods can assist in taking a more holistic problems based approach, limiting unnecessary and complicated interventions.

The research described here has shown that the application of human factors methods can lead to positive changes to the design of proximity detection systems and, more broadly, to develop effective mining vehicle technologies from a user-centred perspective. This provides evidence that the involvement of both end-users and human factors engineers through all stages of the design lifecycle, from concept through to the deployment and evaluation, of a working system is the best way to achieve effective integration of such technologies in mining.

Chapter 5

Overall Discussion, Conclusions and Recommendations for Future Work

5.1 Summary of key findings and contributions to knowledge

This thesis outlined three practical applications of human factors in the mining industry. Each case study applied human factors methods to mining in a way can deliver insights to improve safety through design. In the chapter 1, a number of research questions were outlined for each chapter which represented the original contributions to knowledge. This section will revisit these research questions to summarise what has been learned.

5.1.1 Research outcomes for Chapter 2

In Chapter 2, injury narrative data obtained from surface coal mines in Australia were examined for human factors issues. The two research questions posed in that chapter are discussed below.

What can be learnt about injuries associated with mobile mining equipment from recoding mining injury narratives with a focus of human tasks using the constant comparative method?

From reviewing injury narratives a variety of issues emerged. The most specific issues emerging from this basic analysis included location on equipment and tasks being performed. Though there were some limitations, such as inclusion of injury severity, this single variable method revealed some trends for more detailed human factors analysis. For example, a main finding was that that a significant number of injuries occurred during mobile mining equipment maintenance. Other findings included the over-representation of bulldozers and the large proportion of injuries associated with access and egress. Analysis of this type should not only be standard

in incident analysis, but also the methods of recording incidents should be broadened to encourage richer narrative information to be collected to allow additional trends to emerge.

What is revealed by transforming the recoded injury narratives as a search tool with a graphical output for specific areas of focus?

Whilst the single variable analysis was revealing, the use of multivariable analysis gave a greater contribution to knowledge and revealed practical mitigation strategies. In this analysis, the visual representation of the data made it possible to identify key human factors issues that would allow for significantly greater targeting. This targeting is key to the success of human factors methods in mining, because in order to thrive the application of methods should produce meaningful and practical results. Increasing the chance of finding important issues is therefore key to the ultimate acceptance of such analysis methods. However, producing the visualisations individually was a time consuming process. For this method to thrive it would require a database fronted by a tool that allowed repeated queries and visual representation. This would prove a useful and persuasive tool for many human factors professionals, equipment designers, equipment procurers and mine site operators.

5.1.2 Research outcomes for Chapter 3

Chapter 3 documented the analysis of in-depth interviews of mining equipment operators using the Critical Decision Method (CDM). The decisions the operators made were placed on the decision tree to aid in determining design solutions. The two research questions for this chapter are discussed below.

When the Critical Decision Method is used with mobile mining equipment operators, what does it reveal about incidents that were previously unknown?

It was surprising that such a comparatively simple interview method was able to find issues not contained within original accident reports. The insights provided through the use of CDM would certainly help target design interventions at site. Perhaps the most useful insight for future researchers was from the modification of the method to include drawing the incident on a whiteboard. Once the operators were explaining

incidents including a diagram, the willingness of the operators to engage in discussion and the richness of information dramatically increased. If applied more widely in the industry they could provide insight that would help shape future designs of equipment, tasks and environments.

What is learnt by using The Decision Ladder to represent the cognitive process of mobile mining equipment operators at the time they were involved in an incident that can be used to make design recommendations?

The application of the decision ladder to the CDM generated data was revealing. All of the decisions made by the operators included a shortcutting a full decision making process. This indicates that design solutions that address the immediate environment of the operator could prove more effective than interventions like knowledge-based retraining. However, although there is a meaningful academic contribution to knowledge through combining CDM with the decision ladder, in a practical sense the decision ladder did not offer much more for design solutions than may have been gained by a judicious application of the more common division between skill, rule and knowledge based behaviour. As such, there appears to be a fine line in the practical application of human factors methods between enough simplicity to be applied and enough richness to be accurate. This method was revealing for research, but through application it became obvious that it would be unlikely to be applied widely in mining, at least in the present incident investigation culture that emphasises obtaining results in as short a time period as possible.

5.1.3 Research outcomes for Chapter 4

Chapter 4 was the most holistic chapter of the thesis, because it provided the ability to change equipment in a real operating environment. This mine site access issue is something that has traditionally been very difficult to overcome in mining research. Three research questions relate to this case study. These are discussed below.

When human factors methods are applied to proximity detection systems in mobile mining equipment what design recommendations to prevent collisions emerge?

The human factors methods applied in this study were able to broaden the scope of study to be about 'collision prevention' rather than purely a proximity detection system. Equally, the outcomes of the research provided practical solutions improve the in-cab interface. Examples of the recommendations included changing to an icon based interface, having most recently detected vehicles added first, turning off the system when on the surface because of spurious detection. More complex recommendations included adding a directional element to the interface. With the more investigative task-based human factors tools, other recommendations also emerged. These included identifying many of the elements of the system that were preventing collisions and an understanding of the different types of environmental conditions that might emerge. So the primary lesson learned is that human factors methods that are not reductionist to a single element of the system, but rather force a holistic review including the intersection between operators, their task and the environment gives a richer understanding of the environment that gives greater scope for design interventions.

What can be learnt about the accuracy and effectiveness of design recommendations to prevent collisions at mines by investigating a real collision?

The above research question was not planned before research began. It only emerged because of the occurrence of an high potential accident that fortunately did not result in tragedy. This did provide a opportunity to assess the predictively powers of human factors methods being applied. Each of the barriers of protection and their modes of failure were uncovered in the previous research. Additionally, when applying the knowledge gained in this accident, design recommendations were found that apply not only to the interface, but also other elements of the equipment and operating environment. This is compelling evidence of the effectiveness of human factors methods in being able to identify additional risks in mining equipment operations.

When design changes in a proximity detection system for mobile mining equipment based on human factors methods are implemented, what can be learnt from investigating their acceptance by mobile mining equipment operators?

The changes made to the system interface as a result of this research managed to increase operator acceptance of the revised system. This provides good evidence that human factors methods can lead to design interventions that are both noticeable and positive to experienced operators. Prior to these interventions drivers were found not to have an average positive acceptance of the system. As the original system interface was not ergonomically designed and had poor operator acceptance then it was likely to be not be effective and maybe even distracting. Therefore, this may lead to a hypothesis that the original system would actually increase the chance of a collision. Though this hypothesis would be difficult to prove conclusively, the implicit finding is that a system designed to help a driver make better decisions but being developed and deployed without explicit human factors input can actually be harmful or at best irrelevant. Human factors methods may well therefore be viewed as enhancers to design. Though this is only a single case study, it provides at least one circumstance in which it appears that the methods are essential to ultimate success of the system. With the inability to actually run randomised trials for such equipment, such evidence is nearly as strong as is possible to be obtained in one case study for the use of human factors with mining equipment.

5.2. Links to broader trends in mining human factors

The research contained in this thesis has coincided with increased interest in human factors in mining, especially in Australia and the USA. As part of an analysis of the broad trends in mining human factors, it is argued here that there are three streams of work that link to the research in this thesis. These are, more targeted reviews of individual accidents using human factors methods, individual case studies of methods that could be widely applied, and prospective reviews of human factors issues for mining automation.

5.2.1 Improving accident reporting to include more human factors

Historically in mining, the use of human factors methods in accident investigations was mainly through individual applications by specialists following high-profile mining

disasters. It is certainly appropriate that complex human factors methods be applied in these circumstances. For example, the tragic events of underground explosion at Soma Mine in Turkey that killed 301 workers justify a large scale investigation that includes human factors issues (Korkmaz, 2014).

Therefore, a trend in human factors research is to review collections of individual incidents that are harmful to often only one person at a time but can be cumulatively just as destructive as a major disaster. Specifically, the approach of re-analysing injury narratives with human factors elements, as presented in Chapter 2, is becoming more widespread. For example, similar reviews of have taken place of mining injuries in Kentucky (Evelyn, 2014), maintenance injuries in USA mining operations (Reardon, 2014) and mining and quarrying injuries in Finland (Reiman, 2012). All of these reviews were able to make descriptive conclusions related to human factors, but all only do single variable analysis, meaning that more complex multifactorial issues were not fully explored.

There were also a number of investigations into mining safety issues that either did not have a human factors focus or had insufficient information supplied in accident reports to draw conclusions. These reports provide even less focus for investigation. For example, a large review of mining incidents involving a worker being entangled in, struck by, or in contact with equipment was able to identify the likely equipment involved, but only that the tasks were 'operation' or 'maintenance and repair' (Ruff et. al., 2011). Similarly, a large review of injuries to contractors at American mine sites was able to determine that they had a greater chance of injury than direct employees, but offered very little to direct further research and nothing that would allow for more targeted interventions (Saehr et. al., 2013).

The research contained within Chapter 2 represents a model for both recording and analysing injury statistics in the future. The goal for investigation of incidents should not be merely informative and descriptive. It should also provide directions that can help predict target interventions. Therefore, the research in this thesis is leading an emerging trend to record more precise account of accidents with greater human,

task and environment issues and then to use multivariable analysis target further research and interventions.

5.2.2 A renewed focus on detailed case studies involving human factors

There has been a noticeable increase in the publication of mining case studies involving human factors investigations and interventions involving mining equipment. In other industries case studies may sometimes be seen as a lesser form of publication compared to laboratory type trials. However, as noted by Horberry et al. (2013), the complexity of the mining industry does not easily lend itself to experimental evaluation, so research often tends to be case study based. Some of the reasons that case studies are prevalent has a scientific basis, namely that the variables at each mine site involving human tasks vary so much that controlling for them would be nearly impossible. However, most of the reasons are pragmatic such as the huge distances to remote sites, researcher access issues to mine sites, significant logistics and costs simply accessing equipment and tasks, and the long operational life of equipment. Taking the above into account, in-depth case studies that describe the processes employed, the successes and barriers to success may represent the best chance of designing out accidents (Horberry et al., 2013). This is especially true if the methods involved are adaptable to various circumstances.

There was a significant drop off in published case studies in the 1990s caused by the demise of the British coal industry, once a major centre of human factors in mining research (Simpson et al., 2008). But a resurgent industry, especially the mining boom in Australia, Canada and USA, had brought a slight increase in funds to perform studies and a belief from individual companies that they will see tangible benefits from the research. One of the highest profile examples is the efforts surrounding the Earth Moving Equipment Safety Round Table (EMERST); a collective of global mining companies who aim to use their collective influence to improve the consideration of key safety issues in mining. Central to this focus was the development of the Operability and Maintainability Analysis Technique (OMAT); a tool that involves prioritised task analysis common in many industries (Horberry et al, 2009). The application of this tool at sites, largely lead by the author of this thesis, resulted in the ability to identify issues and generate solutions for issues related to

access and egress of mobile equipment (Cooke & Horberry, 2011; Cooke & Horberry, 2010). Mobile equipment manufacturers considered the tool as beneficial to positively address their current development blind-spots, especially if it involved being able to see the tasks being actually performed (Horberry & Cooke, 2012). The tool has subsequently been developed into EMESRT Design Evaluation for Equipment Procurement (EDEEP) and shown good promise in generating collaboration between mining equipment manufacturers and end users (Wester & Burgess-Limerick, 2013; Burgess-Limerick, Cooke, Joy and Horberry, 2012).

This EMESRT-related work has much in common with the research presented in this thesis; namely that the methods involved are human-centred and mostly widely applicable to a variety of situations. It would be tempting, in an academic sense, to focus solely on individual issues with a more pure experimental design. However, what has been shown by these published case studies is that the industry is more likely to support research if it is widely applicable and creates actual design change. As mining is an industry where the 'knowledge' is not actively passed in academic papers, but through iterative design changes and the stories that go along with them, a case study style of research is likely to lead to the greatest contribution to change.

5.2.3 The increase in automation and mines of the future

One significant future path for human factors is mining equipment automation for the so-called 'mines of the future'. A recent study of key figures in the Australian mining industry came to the conclusion that in advanced mining industries a gradual introduction of automation is already beginning, and will continue to include remotely operated equipment or even 'people-less' mines (Lynas & Horberry, 2011). The transition to automation in other industries has often been difficult. This is because as the scope of automation expands the complexity of the remaining human tasks, primarily of supervision, adjustment and maintenance become more crucial and complex, often limiting the projected effectiveness of the technology (Baxter et. al., 2011). It is for this reason that some have concluded the push towards automation it will fail unless it systematically includes human factors methods and user-centred input (Lynas & Horberry, 2011).

The review of a proximity detection system provides good support for this claim. A relatively simple piece of technology compared to the 'full automation' that may arrive, it was unsuccessful without the application of human factors methods to support the system development and deployment process. This impact is mirrored in a review of eight projects that implemented innovative mining equipment that concluded that human factors issues were poorly addressed and there was little or no reduction in the incidence of injuries (Bourreau-Trudel, 2014). There is a very strong case that the role of human factors professionals must increase if future automation in mining is to be both safe and successful.

5.3 Recommendations of Future Work

Throughout this thesis, recommendations for future work have been proposed. Most of these recommendations have built upon the findings emerging from the three case studies, for example, use multivariable methods to analyse mining injury data, use the CDM to reveal additional insights or study the operational environment to help better design collision detection systems.

However, aside from these specific issues, other broader avenues of future mining human factors research are possible. These include the following five areas:

- i) **Additional research with equipment manufacturers to improve mobile equipment design.** Earlier in this thesis it was noted that there is often a disconnect between designers and actual mine site operational conditions. As mobile mining equipment such as haul trucks are frequently involved in incidents then this may be a priority vehicle type to focus on. One possible approach is the greater use of the 'OMAT' technique (a task-based, risk assessment and design tool) (Cooke and Horberry, 2011). Additionally it would be beneficial to discover what tools manufacturers actually use when designing equipment, and what additional user-centred design assistance they would they like.
- ii) **Expand work human factors work into process plant maintenance and design.** Little mining human factors work has been conducted examining minerals processing (Li et al, 2011), so extending the mobile mining equipment design methods to this domain might be beneficial.

- iii) **Focus on automation.** As noted earlier in this thesis, mining automation is increasing. The research in this thesis with proximity detection systems has shown that human factors input can assist with this low level automation system. However, it is likely that there will be significant human factors challenges with full automation. These issues include: operator acceptance, skills retention, maintenance issues and abnormal operations (Lynas et al, 2011). This is a huge area that human factors input has helped in other industries such as aviation or healthcare, so the mining industry learn valuable lessons from them.
- iv) **A focus on performance, not just safety.** Consider moving away from only addressing safety and into performance improvement. Most recent mining human factors work has emphasised safety, but a greater consideration of possible performance efficiency issues from the application of a user-centred focus may be extremely beneficial (Horberry et al, 2010). Similarly, moving the prevailing minerals industry mind-set to 'reliability' rather than safety may be advantageous. Safety culture is a related area where benefits can be obtained, but this does not preclude the basic need for fit-for purpose equipment, technologies, tasks and systems. A difficulty arises if a focus on safety culture results in a reduced focus on the design of equipment (Rollenhagen, 2010). This is because the focus on safety culture, arguably, overlooks considering design directly. Rather it favours strategies that focus on social and individual elements of the system such as beliefs, values and attitudes especially in situations where design changes are costly (Rollenhagen, 2010).
- v) **Develop simple methods.** As the mining industry is highly time constrained, then developing and applying simple methods that are widely applicable would be beneficial, rather than more complex methods that are not widely used (Cooke and Horberry, 2010).

5.4 Conclusions

The three studies described in this thesis have produced both academic contributions to knowledge and practical benefits. The research could be built on through the five further research areas mentioned above. In the past, human factors

work in the mining industry has often been 'stop-start' (Simpson et al., 2009). However, there is a nascent development whereby the mining industry is beginning to see the value of a user-centred approach (eg EMESRT).

It is contended here that the research contained in this thesis can be seen as an early step for the widespread use of human factors-style approaches in the minerals industry. Difficulties such as obtaining continuing funding, obtaining mine site access and having a pool of experienced mining human factors researchers will always be challenges. However, the vision of a global minerals industry that has safe, effective and integrated operations involving equipment, systems and people is a worthy one to aspire towards.

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Appendices

Appendix 1: Incident Analysis Findings linked to Chapter 4

Appendix 1.1 Incident time-line


The information gained from the CDM interviews was placed in the below table which shows:

1. A sequence of events placed in chronological order, called a **TIME CHUNK**.
2. The time chunks below from the perspectives of the **LOADER OPERATOR** the **SERVICE VEHICLE OPERATOR** and the **LIGHT VEHICLE OPERATOR** are displayed.
3. A **BARRIER FAILURE** is shown when it occurs. A barrier is a layer of protection or risks control implemented or naturally existing that could have prevented a collision.
4. The **FAILURE MODES** that occurred are noted.

Table A1: Proximity Detection Incident Analysis

TIME CHUNK	LOADER OPERATOR REPORT	SERVICE VEHICLE OPERATOR REPORT	LIGHT VEHICLE OPERATOR REPORT
1	Loader Operator called service truck and raised meeting at workshop (re-fuelling). Notified by service truck they would arrive in 10-15 minutes.	Received call from bogger operator and notified them that they would be at the workshop in 10-15 minutes.	

TIME CHUNK	LOADER OPERATOR REPORT	SERVICE VEHICLE OPERATOR REPORT	LIGHT VEHICLE OPERATOR REPORT
2		<p>Asked water cart operator, who had just completed watering, if road to U/G was in okay condition. It can be slippery for the service vehicle following a watering. Was informed that the road was okay.</p>	
3	<p>Went to workshop and got there about 4-5 minutes before service truck. Timing confirmed by the proximity detection system log.</p>		
4	<p>Waits for service truck whilst filling out paperwork. Truck was in idle.</p>	<p>Service truck travels UG and is calling levels on descent to meet loader operator</p>	<p>LV driver was coming up the Crown Decline and reportedly calling levels.</p>
5	<p>Heard the radio in the workshop (loud speaker) with a 'chat' type conversation. This prompted operator to check that his radio was on channel 1. Reports that he clearly remembers his radio being on channel 1.</p>		
6			<p>When approaching the level of workshop, reportedly called "LV 2019 up".</p>

TIME CHUNK	LOADER OPERATOR REPORT	SERVICE VEHICLE OPERATOR REPORT	LIGHT VEHICLE OPERATOR REPORT
A	<p align="center">BARRIER FAILURE - RADIO CONTACT</p> <p align="center">Call of LV Location was not heard, incorrectly interpreted or forgotten by Bogger operator.</p>		
7		<p>Service vehicle calls location and direction at stockpile 10. Stockpile 10 is near the workshop and commonly the last level called before reaching the workshop.</p>	<p>LV driver heard service truck calling "Service Vehicle 10 Down" indicating that they were going past stockpile 10.</p>
8		<p>Service truck arrives at the area and drives across workshop entry, to check if the loader is there.</p>	
9	<p>Sees service truck arrive at workshop. At this time a proximity detection alarm flashes on the screen and reportedly notices the alarm. The alarm is likely to be that recorded at 11:38:51am</p>		
B	<p>BARRIER FAILURE – Proximity detection</p> <p>The proximity detection that went off when the service vehicle operator was in vision of the loader operator was not the service vehicle, which shows as LC449 on the screen.</p> <p>The approaching light vehicle which shows as the similar which shows as LV685.</p> <p>This incorrect interpretation was made further likely as the screen for the proximity detection screen is to the right of the driver and they look to the left to look over the bucket of the loader.</p> 		

TIME CHUNK	LOADER OPERATOR REPORT	SERVICE VEHICLE OPERATOR REPORT	LIGHT VEHICLE OPERATOR REPORT
10		Notifies loader is in workshop and halts because he needs to access the rear of the workshop area where there is a park up bay.	
C	BARRIER FAILURE – VEHICLE SERERATION Workshop design forces loader to exit into the main decline if service vehicle arrives.		
11		Communicates to loader driver visually & with hand signals that he will back up the decline to allow the loader operator to exit workshop.	
D	BARRIER FAILURE – RADIO Service Vehicle Operator does not radio to loader operator which would have alerted light vehicle		
12	Sees hand signals from service truck operator and indicates with hands that he understands (thumbs up).		
E	BARRIER FAILURE – RADIO Loader operator does call that he is exiting the workshop.		
13		Started reversing up decline to stop blocking workshop entrance and get out of road of loader operator	
14	Raised bucket so that it does not scrape the ground when exiting the workshop and started to move loader forwards to exit the workshop.		

TIME
CHUNK

LOADER
OPERATOR REPORT

SERVICE VEHICLE
OPERATOR REPORT

LIGHT VEHICLE
OPERATOR REPORT

BARRIER FAILURE – VISION

With the bucket up operator could not see the light vehicle as shown in the below left image, where an LV is in the decline in the approximate position of collision. The top of this LV can, just barely, be seen in the below middle image in the red box. The below left image show the position of this LV in the images.

F



15

Loader operator also had light on when exiting the workshop shining into the intersection and an already backlit powerbox.

TIME CHUNK	LOADER OPERATOR REPORT	SERVICE VEHICLE OPERATOR REPORT	LIGHT VEHICLE OPERATOR REPORT
G	<p align="center">BARRIER FAILURE - LIGHTS</p> <p>A combination of the backlit power-box area and the loader lights mean that the lights of the LV were not seen by the loader operator.</p> <div data-bbox="600 456 1102 788" data-label="Image"> </div>		
16	<p>As the LV operator reached the workshop level saw the service truck. Slowed to allow the Service Truck to enter the workshop.</p>		
17	<p>Noticed the light vehicle was approaching and dimmed head light and reversed back up decline in order to move closer to wall and allow light vehicle to pass.</p>		<p>Light Vehicle Operator continues to roll towards workshop entrance slowly, still thinking that the service vehicle will enter the workshop.</p>
H	<p align="center">BARRIER FAILURE – Lights</p> <p>The light vehicle operator did not see the lights of the loader coming out of the workshop.</p>		

TIME CHUNK	LOADER OPERATOR REPORT	SERVICE VEHICLE OPERATOR REPORT	LIGHT VEHICLE OPERATOR REPORT
18	As the loader operator is moving forwards towards this exit. At or around this time the proximity detection alarm goes off and the screen flashes for the service vehicle but is not seen by the loader operator.		Noticed that the service truck had its park lights on (rather than full headlights) and was not moving forwards.

BARRIER FAILURE – Proximity Detection

As the proximity detection goes off the driver could have been made aware that a *second* vehicle was in the proximity. Even though he had misinterpreted the first vehicle. However, the screen is mounted to the rear of the operator when travelling forwards and would not be seen. The volume was turned down so would not be heard. The operator may have seen the flash of the vehicle coming up in the windscreen but noted it is likely he would have continued to have interpret this as the service vehicle, as the flash continues.

19		The LV operator eventually pulled up approximately 3m from the intersection with the workshop.
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BARRIER FAILURE – LV Position

It is reported to be procedure that vehicles should pull up at least 10m before an intersection. The LV operator pulled up much closer than this to the intersection.

20	Bucket of loader starts to exit workshop and loader operator turn down decline.		Immediately or very close recognising that something 'might' be coming out of the workshop the LV operator notices the bucket of the bogger.
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TIME CHUNK	LOADER OPERATOR REPORT	SERVICE VEHICLE OPERATOR REPORT	LIGHT VEHICLE OPERATOR REPORT
J	<p>BARRIER FAILED – Lack of Pause at Intersection</p> <p>Rather than pausing when entering the main decline and dimming lights, (as normal) he continued. A pause may have allowed the time for the operator to escape.</p>		
21	<p>Hear service truck using the horn. Loader operator thinks he looked back at the Service Truck but kept going.</p>	<p>Used horn to try and alert operator</p>	
K	<p>BARRIER FAILURE – Horn</p> <p>Loader operator did not interpret horn as a signal to stop, or at least had not interpreted it in time to prevent collision</p>		
22	<p>Cannot remember hearing any radio calls from the service truck or the LV.</p>	<p>Tried to call driver on 2-way.</p>	<p>Tried to call driver on 2 way “Bogger! Bogger! Stop! Stop!”) and begins to reverse. – noted that his calls were</p>
L	<p>BARRIER FAILURE – Radio</p> <p>Radio calls are not heard by or fail to reach Loader operator. This would be possible if the radio was on the wrong station, the volume turned down or the radio transmission faulty.</p>		
23			<p>The LV operator attempts to back away from loader but contacts the wall.</p>
M	<p>BARRIER FAILURE – Physical Intersection Design</p> <p>In many situations the LV operator could have continued to reverse away from the loader. However, in this situation the LV operator did not have much time to react calmly to the loader approaching and contacted the wall. The driver could, therefore, not continue to take evasive action. If the road was straight around the workshop colliding with the wall would be much less likely.</p>		

TIME CHUNK	LOADER OPERATOR REPORT	SERVICE VEHICLE OPERATOR REPORT	LIGHT VEHICLE OPERATOR REPORT
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LOADER BUCKET CRASHES INTO THE HOOD OF THE LIGHT VEHICLE PUSHING IT AGAINST THE WALL

24	Felt impact of hitting LV – soft impact – and knew that it was not the wall – harder and common impact.		
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BARRIER SUCCEEDS – Bonnet of Ute
 Bonnet of ute is struck before passenger in LV. This is the last physical control before the bucket of the loader had struck him.

Had the bucket been raised approximately 300mm higher the first impact would have been with the windscreen of the LV. The approximate impact point is highlighted in the below image.

N



25	After collision paused and lowered the bucket. Saw rear of LV.
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TIME CHUNK	LOADER OPERATOR REPORT	SERVICE VEHICLE OPERATOR REPORT	LIGHT VEHICLE OPERATOR REPORT
26	Raised bucket and reversed away from light vehicle back into workshop		
27	Saw that LV operator had exited the vehicle and dropped bucket.		LV operator gets out of vehicle and waves at loader operator.
28	Heard radio calls from LV operator notifying supervisors and surface		Called supervisors of surface to notify them of collision.
29			Approaches loader and loader operator, asks how he did not hear his radio calls. LV operator checks radios.

(end of time-line)

Appendix 1.2 Analysis

As can be seen in the above time sequence a large number of current barriers failed to allow this collision to occur. Some types of barriers failed multiple times. The primary barriers that failed, and recommendations for improvement are shown below:

	Barrier	How Barrier Failed	Recommendations
1	Radio Contact	<ul style="list-style-type: none"> · Not calling exit of workshop. · Calls not heard by loader either through <ul style="list-style-type: none"> o Noise; o radio blackspots; o selection of the wrong channel; o or volume turned down. 	<ul style="list-style-type: none"> · Reinforce calling, especially calling when exiting the workshop. Potentially install a sign to call as a reminder upon workshop exit. · Increase ease of visibility of radio volume. A number of person on-site noted they have accidentally left the volume down on their radios from time to time.
2	Lights up walls	<ul style="list-style-type: none"> · Area was backlit. · Loader operator did not dim lights when exiting intersection. 	<ul style="list-style-type: none"> · Turn off power to powerbox. The powerboxes were noted to be lit because they are usually on the side of the walls of the decline. This one is recessed into the wall and there does not appear to be a reason that it needs to be lit unless somebody is working in the area. · Reinforce practice of pausing and flicking lights down when approaching intersections.

3	Vision	Driver had to drive fwds with bucket high	<ul style="list-style-type: none"> · Consider how vision could be increased. · A fwd facing camera may improved vision when the buck needs to be raised.
4	Intersection Design	The loader needed to go out into the decline in order to allow the service vehicle to the rear of the workshop. This, therefore, triggers the situation to occur.	Consider placing another 'cut in the workshop for the service vehicle in front of where the loader goes. This means that it may not matter if the service vehicle arrived after the loader, as it would simply choose the forwards parking bay. It is noted this may not be financially feasible.

5	Proximity Detection	<ul style="list-style-type: none"> · Proximity detection system did not pick up vehicles consistently. · The second vehicle was missed. · It was noted in testing of the recreated position that the loader did not see the light vehicle used in recreating on the proximity screen until it was through the intersection on both sides. 	<ul style="list-style-type: none"> · Consider placement of proximity system and place it where the driver will be facing with the most common vehicle interactions. · Consider changing interface design so that light vehicles and service vehicles can be more easily distinguished (rather LV and LS). · Consider changing audible alarm from continuous until acknowledged to a shorter alarm that does not need to be acknowledged by touching the screen (eg. alarm for 5 second from detection and say vehicle type). This will limit the temptation to turn down the volume. · Reinforce variability of proximity detection system. · Test the sensitivity of all mounted proximity detection tags onsite.
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