Automation Experience with a Global Perspective – An Assessment of the Automation Impact on Worker Safety and Health

Final report - November, 2023

Prof Joel Haight - University of Pittsburgh

Prof Robin Burgess-Limerick - The University of Queensland

Project funded by NIOSH under BAA 75D301-20-R-67845, contract 75D30120C09628

Executive Summary

Mines internationally are implementing autonomous and semi-autonomous equipment. While the overall impact of increased automation is likely to be improved safety and health, autonomous equipment brings new risks, and autonomous components are currently being integrated into existing systems without a complete understanding of the impact on the humans in the system. The focus of this research is to improve understanding of the current state of autonomy in mining from a global perspective to ensure maximally positive safety and health outcomes from future deployments.

Information was obtained through a review of relevant literature, and relevant standards and guidelines, and a review of incidents associated with automation. Visits were undertaken to 10 mines in Australia, Chile, Sweden, and the USA. While researchers were unable to visit Canadian mines, conversations were held with automation experts from the Canadian oil sands industry. While not directly related to this project, researchers also visited mines in South Africa and Brazil, evaluating their transition to automation as well. Interviews and focus groups with mining company staff provided insights, as did participation in relevant conferences and forums in Australia, Chile, and the USA, and facilitation of the NIOSH Automation and Emerging Technologies Partnership and LinkedIn Workgroup.

Considerable safety and health benefits of removing miners from exposure to health and safety hazards through automation are evident. Automation also provides increased productivity through increased consistency of equipment operation and increased equipment utilization rates. Ensuring equipment operation always remains within specifications reduces wear.

However, the introduction of automated components introduces new failure modes that mine operators should understand and manage, including software shortcomings, communication technology disruption, cyber security breaches, unauthorised access to autonomous zone, loss of manual skill, over-trust, input errors, inadvertent mode changes, complex interactions, sensor limitations, lack of system awareness of environment, loss of situation awareness, distributed situation awareness challenges, communication difficulties, workload, and musculoskeletal injury risk factors. Acceptance of automation is not universal.

Effective risk management requires analysis of these potential unwanted events during system design. The analyses undertaken should include task-based risk assessments involving a range of operators and others affected by the system, and systems-based techniques, in addition to conventional hazard-based risk analysis techniques. As far as possible, the risks should be reduced during system design. Residual risks need to be understood by mine management to allow effective controls to be devised, implemented, and monitored.

While the standards and guidelines that have been provided to assist the implementation of automation in mining may be helpful, the extant documents are incomplete in that insufficient attention has been paid to the integration of humans and technology within the resulting joint systems. Human systems integration processes adapted from other industries should be implemented during acquisition of automated mining equipment.

Opportunities for further research include; case-studies of the implementation of automation at USA mines, assessment of the use of systems-based risk analysis methods, human-in-the-loop simulation to improve interface designs, investigations of teamwork and decision making, and the design and evaluation of training and competency assessment methods. Cultural issues related to the acceptance of automation within the USA also deserve attention.

Table of Contents

Introduction

Problem statement

Mines internationally are implementing autonomous and semi-autonomous equipment including trucks, blast-hole drill rigs, and dozers at surface mines; and loaders, trucks, and drills in underground metal mines. Semi-autonomous longwalls are also in operation at underground coal mines. While the overall impact of increased automation is likely to be improved safety and health, autonomous equipment brings new risks; and autonomous components are currently being integrated into existing systems without a complete understanding of the impact on humans. The focus of this research is to improve our understanding of the current state of autonomy in mining from a global perspective to ensure maximally positive safety and health outcomes from future deployments in the USA.

Global mining automation installations

Based on publicly reported information collated by Lynas et al (2023), there were 183 installations of autonomous (and semi-autonomous) mining equipment fleets by 2022 (Figure 1). Australian mines hosted 44% of the installations, with Canadian mines being the next most common venue (16%). The most common fleet types were autonomous surface haul trucks and semi-autonomous underground Load-Haul-Dump vehicles, followed by autonomous surface blast-hole drill rigs. The majority of Australian installations were at surface mines (64%) while the majority of Canadian installations were at underground mines (62%).

The sizes of surface truck fleets are typically larger than other equipment types. According to data collated by FutureBridge (2022), the total number of autonomous haul trucks in operation globally in 2022 was 1070 (an annual increase of 39%), of which 706 were operated in Australia. The number of autonomous trucks in operation globally is forecast to exceed 1800 by the end of 2025.

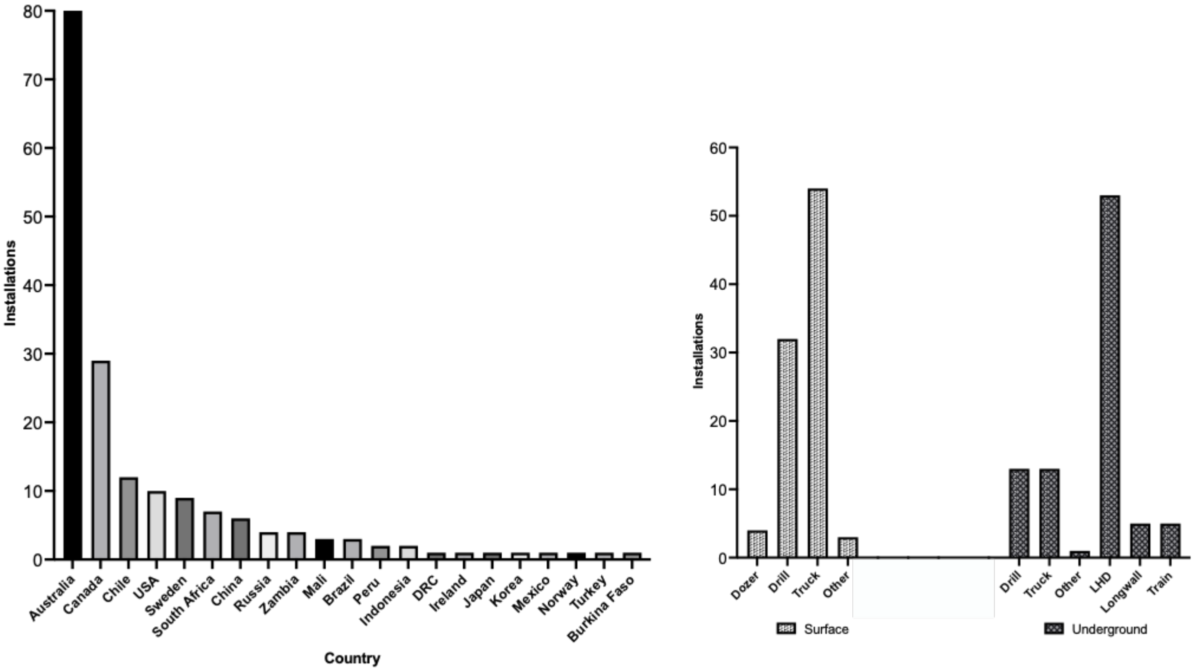


Figure 1: Installations of automated mining equipment fleets to 2022 by country and equipment type (N=183). "Installations" includes trials of autonomous equipment.

Methods

Research describing the progress of mining automation over the last 25 years was summarized with a focus on the anticipated safety and health benefits, and the potential adverse impacts of automation on safety and health. Information regarding incidents associated with automated mining equipment was sought internationally. The only jurisdictions from which detailed information describing incidents associated with mining automation were available were Australian. Company comparisons of incidents post-automation installation were also obtained.

Site visits were undertaken to:

- Four surface mines in Australia to observe autonomous trucks, drill rigs and dozer
- Two Australian underground mines to observe semi-autonomous LHD and an autonomous longwall
- A Swedish underground mine to observe autonomous train and semi-autonomous LHD
- An underground metal mine in Alaska
- Two Chilean surface mines to observe autonomous haul trucks and drill rigs
- Two Chilean remote operating centers

Interviews and discussions were undertaken with a range of staff at each site. Further discussions were held with corporate staff, including a focus group undertaken attended by staff from three multi-national mining companies with responsibility for autonomous haul truck safety, as well as representatives of several equipment suppliers.

The researchers attended and presented at a range of relevant conferences and forums:

- SafeMining 2022. 2nd International Conference on Safety and Labor Health in Mining. June 8-10, 2022. Virtual.
- AusIMM Minesafe International Digital Conference. September 21-22, 2020. Virtual.
- Robotics & Automation in Mining. Dec 3-4, 2020. Brisbane.
- GMG/Austmine Innovation forum August 17 & 18, 2022. Perth.
- Equipment manufacturers association (AEM/AEF) meeting, 2022. Milwaukee, WI
- World Mining Congress, June 26-29, 2023. Brisbane.
- Minería Digital 2023 - 10th International Congress on Automation, Robotics and Digitalisation in Mining. August 9-11, Santiago.
- GMG Innovation forum, August 29-30, 2023. Brisbane.

Following on from a workshop held by the Mine Safety and Health Research Advisory Committee on *Emerging Technologies in Metal Mining* held in Denver in September 2018, an *Automation and Emerging Technologies Partnership* serving NIOSH and the mining industry was facilitated.

The specific goals of the partnership are:

- Provide a forum for providing input on health and safety concerns, research gaps, and technologically and economically feasible technical direction with respect to automation, collision avoidance, and other emerging technologies.
- Provide a forum for review, evaluation, and discussion of specific technical and scientific questions. This includes identifying existing controls and best practices used by mine operators and other industries to minimize mine worker exposure to hazards associated with automated machines and maximize the benefits of new technology.
- Provide a forum for the exchange of the scientific findings on the implementation of automation technologies on mobile equipment, including full and supervised autonomy, and collision avoidance systems for surface mining equipment.
- Provide a forum for industry, manufacturers, academia, and others to present their research, system development, testing, and implementation activities and progress.

Four partnership meetings were conducted: October 8-9, 2020; August 17-18, 2021; September 14-15, 2022; September 20-21, 2023. Minutes and presentations, and information about future meetings are available via https://www.cdc.gov/niosh/mining/content/automationpartnership.html

Mining automation literature

Twenty-five years of improving health and safety through automating mining equipment

Since the field of automation in the mining industry is relatively new, the research literature search was not limited in scope using any other scope defining key words than mining industry and automation. The familiarity the researchers have in this field and their long experience has allowed determination that the literature was adequately included in the review. The search was, however further refined by focusing on the literature associated with the research around the human interface with the automated systems. There were more than 150 journal articles cited here. In addition, the researchers cited more than 10 standards.

While almost certainly not the first to do so, Corke et al (1998) highlighted the potential for “advanced robotics systems” to reduce exposure of miners to fatality and injury risks, as well as health hazards such as noise, vibration, dust and diesel particulates. — This assertion has been frequently repeated as a motivation for automating mining equipment (eg., Corke et al., 2008; Fisher & Schnittger, 2012; Knights & Yeates, 2021; Lever, 2011; Ralston et al., 2015; Marshall et al., 2016; Paredes & Fleming-Munoz, 2021; Thompson, 2014).

Corke et al (1998) went on to describe progress towards vision-based control for automation of draglines and underground hydraulic manipulator arms (for a secondary rock-breaker, for example). The same Australian CSIRO researchers also described progress towards automation of underground Load-Haul-Dump (LHD) vehicles and again noted the potential safety and health benefits as motivation for the work (Roberts et al., 2000).

Contemporaneous research at the Pittsburgh Research Center of the US Bureau of Mines (subsequently NIOSH) focussed on navigation for non-line-of-sight remote control of underground coal continuous mining machines with the aim of removing miners from hazardous situations (Schiffbauer, 1997). Efforts directed toward developing autonomous continuous mining equipment have continued however, success remains elusive (Reid et al., 2011; Ralston et al., 2006; 2014; Dunn et al., 2015). That said, automated functions for continuous mining machines including heading control, and a “follow me” function that allows a flexible conveyer train being loaded by a continuous mining machine to autonomously match it’s speed have recently been introduced (Cressman, 2023). It has been suggested that shuttle car automation in underground coal mines is a possibility (Corke et al., 2008). However, despite recent research on the topic (Androulakis et al., 2019; Ralston et al., 2017) this promise also remains as yet unfulfilled; as does the automated bolting required for automated roadway development (Leeming, 2023; Meers et al., 2013; van Dun et al., 2013). LaTourette & Regan (2022) provide a discussion of the barriers facing the introduction of new technology in general in the USA underground coal mining industry, only some of which are technical.

Greater success has been achieved in the automation of underground coal longwalls using a combination of inertial navigation, LIDAR, and camera systems (Boloz & Bialy, 2020; Dunn et al., 2023; Peng et al., 2019; Ralston et al., 2104; 2015; 2017; Wang & Huang, 2017; Xie et al., 2018). Miners located at the face during longwall operation are exposed to major safety and health risks including explosion risks, noise, and dust exposure (e.g., Brodny & Tutak, 2018). Removing miners from vicinity of the face via remote monitoring and automation has considerable safety and health benefits and operating longwalls with remote supervision is becoming routine at several Australian mines (Dunn et al., 2023; Gleeson, 2021; 2022). The implementation of “fully automated underground mining face cutting” has also been reported at a Chinese underground coal mine (Gleeson, 2023).

While technical challenges were the primary focus during the early development of autonomous trucks and LHD for underground metal mines, safety considerations also received attention (eg., Dragt et al., 2005; Duff et al., 2002; Scheding et al., 1999; Swart et al., 2002). By 2006, automated trucks and semi-autonomous LHDs were in use at the De Beers Finch underground diamond mine in South Africa (Burger, 2006). Safety of the system was achieved through an access control system that prevented unauthorised access to the automated production area. Removing system controllers from the manual loaders to a control room was noted to reduce occupational injuries.

Automated trucks and semi-automated LHD are now widely utilized in underground metal mines (eg., Burgess-Limerick et al., 2017; du Venage, 2019; Moreau et al., 2021; Vega & Castro, 2020). The safety and health benefits of removing miners from these underground vehicles is clear (e.g., Paraszczak et al., 2015). Exposure to musculoskeletal hazards including whole-body vibration are eliminated, as are vehicle collision risks, and head injuries associated with LHD buckets catching the rib while tramming. A 16-20% reduction in exposure to diesel particulate matter has been estimated to be associated with the introduction of automation to underground copper mines (Moreau et al., 2021). Loader productivity is increased by about 24% (Dyson, 2020). Research towards automation of the loading phase of LHD operation has been undertaken (Tampier, 2021; Wei et al., 2022) and major manufacturers are offering autonomous bucket filling to allow fully autonomous LHD operation (e.g., Leonida, 2023).

Automated drills and trains are also utilized in underground metal mines with safety and health benefits (e.g., Hariyadi et al., 2016; Li & Zhan, 2018; Quinteiro et al., 2001; Thompson, 2014; Valivaara, 2016). Automated charging of underground blast-holes has also been demonstrated (Taylor, 2023). Perhaps the most fully automated underground mine is Resolute Mining's Syama gold mine in Mali where autonomous drilling, loaders, and trucks are all utilized (Dyson, 2020).

At surface mines, dragline automation research (Winstanley et al., 2007) initially aimed to provide operator assist rather than operator replacement. The researchers recognised the importance of skilled operators and sought to augment their abilities by automating the repetitive aspects of the task. Later, Lever (2011) suggested that dragline automation was technically feasible and that its introduction was only a matter of time. However, it has become evident that removing dragline operators by automation is not being entertained (Marshall et al., 2016) nor is there a strong safety incentive to do so.

Considerable research has been undertaken towards the automation of excavators (eg., Dunbabin & Corke, 2006; Stentz et al., 1999) however it seems that the cost and risk of introducing automated diggers to mining operations was perceived to outweigh the benefits (Lever, 2011) and the current automation technology is restricted to "operator assist" functions (Dudley & McAree, 2016). Despite the promise of improved productivity (Yaghini et al., 2022) automated excavators and shovels do not appear to be on the horizon. There is not a strong impetus from a safety and health perspective, although technology that reduces the risks of excavators striking truck trays during loading would have safety benefits for manual truck operators.

The development of autonomous haul trucks for surface mines commenced in the mid-1990's (Nebot, 2007) with the first commercial deployments occurring in Chile and Australia in 2008. Significant cost savings, productivity improvements, and risk reductions were anticipated (Bellamy & Pravica, 2011; Lever, 2011) and these claims appear to have been achieved (e.g., GMG, 2021; Perry, 2022; Price et al., 2019). The use of autonomous haulage at surface mines has proliferated internationally across a range of commodities including iron ore, coal, gold, and oil sands. Simulation studies suggest that even greater productivity gains may be obtained by automating smaller trucks (Redwood, 2023). Water carts are also being automated for use on surface mine sites (Westrac, 2023) as are light vehicles (Cholteeva, 2021).

Automated blast-hole drilling was under development in 2006 (Lever, 2011). The first fully automated production bench drilling was achieved at a surface mine in Australia in 2014 and has become increasingly common (Morton, 2017; Onifade et al., 2023). By 2021, Rio Tinto operated 26 autonomous drills (GMG, 2021). Work is underway to automate the scanning of blast holes and the explosive trucks that subsequently charge the blast-holes (Knights & Yeates, 2021).

Dozer automation research commenced as early as 2006 (Lever, 2011). Considerable subsequent work has been undertaken to develop a system that is capable of autonomously undertaking bulk push overburden removal (see Dudley et al., 2013; Marshall et al., 2016; McAree et al., 2017). This technology is used within Caterpillar's Semi-Autonomous Tractor System in operation at a small number of sites. Both productivity and safety benefits are claimed (e.g., Theiss, 2021; Westrac, 2023). The productivity benefits are derived from increased utilization. Removing dozer operators from the musculoskeletal hazards associated with manual dozer operation (Lynas & Burgess-Limerick, 2019) is certainly beneficial from an operator health perspective, and has potential to facilitate increased workforce diversity. Removing operators from dozers undertaking high risk tasks such as on stockpiles would also be beneficial, although in the short-term this is more likely to be achieved via remote control rather than automation (eg., Moore, 2023a; Chan, 2022).

While not strictly mining equipment, automated train loading and unloading has been in place at surface mines for some years and, after many years of effort, Rio Tinto's autonomous train delivered its first iron ore 280 km from mine to port in 2018 (Rio Tinto, 2019). BHP commenced testing of autonomous ship-loaders at Port Hedland in 2022 (BHP, 2022).

Mining automation risks

While automation has considerable potential to increase safety by removing people from exposure to hazards, the potential for new hazards to be introduced has also been identified (eg., Atkinson, 1996; Benlaajili et al., 2021; Chirgwin, 2021a; Lynas & Horberry, 2011; Gamer et al., 2021; Ghodrati et al., 2015; Ishimoto & Hamada, 2020; Ninness, 2018; Pascoe, 2020; Pascoe et al., 2022a; 2022b; 2022c; 2022d; Rogers et al., 2019; Tariq et al., 2023). These hazards include new failure modes associated with sensor failure, calibration errors, software errors, communication breakdowns, or interaction between automated systems and mechanical or electrical failures. Software errors can also be introduced during upgrades, and cybersecurity risks are created. Human error associated with loss of situation awareness, mode errors, or input errors are also possible. Behavioral changes in response to the introduction of autonomous components brought about by over-trust or under-trust can compromise anticipated safety benefits. The opportunity for human supervisors within the system to be overloaded was also noted, with potential impacts on control room operator health. The importance of adequate training was highlighted. Replacing field-based operators with supervisors located in a control room also means a loss of access to the information previously available to the field operators, which may contribute to delays in identifying abnormal events. The importance of well-designed and maintained haul roads has been identified as a key safety requirement for autonomous haul trucks (Benlaajili et al., 2021; Thompson, 2011).

The complexity of systems that combine automated and human elements results in situations in which adverse outcomes can arise in the absence of the failure of any element of the system (Leveson, 2012). The consequence is that conventional failure-based risk analysis methods may not be sufficient to understand the risks associated with the introduction of autonomous components. Hassall et al (2022) provide examples of the use of two traditional methods (Preliminary Hazard Analysis & Failure Mode and Effects Criticality Analysis) and two alternate methods (Strategies Analysis for Enhancing Resilience & System-Theoretic Process Analysis) for identifying human-system interaction risks associated with automation in mining. Each technique identified potentially hazardous human-system interactions and each had strengths and weaknesses. A hybrid or combination approach was suggested. Cummings (2023a; 2023b) has also pointed out that systems that utilize non-deterministic artificial intelligence or machine learning can fail in unexpected ways, and require new systems engineering processes to ensure the implications for safety are understood.

Marshall et al., (2016) identified challenges for the deployment of robotic systems in mining as including reliability, and fail-safe operation with graceful failure; the design of human-machine interfaces; and safely managing the colocation of robots and humans; while Burgess-Limerick (2020) highlighted the following safety-related human factors issues associated with the introduction of automation to mining:

- Inappropriate reliance on a human "safety driver" during development or testing
- Degradation of manual skills
- Loss of situation awareness leading to delayed or inappropriate response to abnormal situations
- Nuisance alarms, leading to failure to respond to abnormal situations
- Errors during human input to automated components, including mode error
- Increased span of control
- Fewer operators leading to decreased probability of abnormal event detection
- Supervisor cognitive overload
- Over-trust
- Under-trust, or deliberate circumvention of automation

These potential issues highlight the importance of ensuring that human characteristics and limitations are considered during the implementation of automation (Horberry, 2012; Horberry et al., 2018). The promised safety and health benefits of automation will only be realized if the joint system that emerges from the combination of human and automated components functions effectively.

Mining automation incidents

Western Australian database

The Western Australian Department of Mines, Industry, Regulation and Safety provides access to a database[1] of "summaries for industry awareness" describing incidents reported to the regulator from January 2010 to May 2021. Sixty-one incidents involving automated mining equipment were identified within the database. Fifty-three of the incidents involved autonomous surface haul trucks, while eight involved surface drill rigs.

Autonomous drill rig incidents

Two autonomous drill rig incidents involved smoke or fire occurring on the rig, while the remaining six occurred during tramming. Of these, in two cases the rig collided with a windrow or trough; in three cases a collision, or near collision, occurred with another drill rig; and in one case the autonomous drill rig collided with a light vehicle. Where contact between vehicles occurred, the cause of the failure of the drill rig's obstacle avoidance system are typically not explained. For example, the summary of one incident reads:

> "At an open pit, an autonomous mobile drilling rig was proceeding to a new drill pattern location. During the journey, the machine made contact with a parked light vehicle (LV). The drill was stopped and a supervisor informed. No injuries were sustained. The remainder of the autonomous fleet was made inactive while hazard detection systems were tested for effectiveness. An investigation was commenced." SA-762-28966, 9/10/2018

While drill rigs are slow moving and hence the probability of a high consequence collision is low, the incident summaries highlight that obstacle avoidance technologies are fallible.

In another case, an input error in the location of the autonomous boundary was noted as a cause of the incident, ie:

> "An autonomous drill boundary at an open pit was updated to allow an autonomous drill to be relocated to another area of the drill pattern. While relocating, the autonomous drill crossed the cone-delineated boundary into a manned drill area. Workers in the vicinity saw the autonomous drill behind a manned drill and called the control room operator to stop the autonomous drill tramming. It stopped about 15 metres from the manned drill. The supervisor was notified and both drills stopped work. There were no injuries and an investigation was commenced. *It was found that the updated autonomous drill boundary was incorrect*." (*emphasis added*). SA-554-27908, 27/5/2018

This is an example of error during input to the control system, which is a general category of potential errors associated with the introduction of autonomous components.

Autonomous truck incidents

Some of the incidents reported were unrelated to the autonomous functions of the truck. In three cases, the incidents occurred while an autonomous truck was being operated manually. One of these incidents may have been the results of loss of manual driving skill.

> "At an open pit, an autonomous haul truck was being inspected and calibrated. During the operation, a worker manually drove the truck a short distance and parked it. The truck continued to roll forward and made contact with a light vehicle (LV). A supervisor was informed. No injuries were sustained. An investigation was commenced." SA-491-27100, 09/02/2018.

In one case, smoke was noticed coming from the tyre of an autonomous truck, and in another, an autonomous truck was struck by lightning.

---

[1] https://www.dmp.wa.gov.au/Safety/What-accident-and-incident-19287.aspx

> "An empty autonomous mining truck (AMT) was ascending a ramp at an open pit when it was struck by lightning. A nearby worker witnessed a tyre exploding and causing damage to the upper structure (including the deck, autonomy cabinet, engine and cab) of the AMT. An emergency call was transmitted and all AMTs on site were stopped. A 400-metre exclusion zone was established and personnel evacuated from the area. There were no injuries. Investigations found that the lightning strike initiated a chemical explosion that caused the uncontrolled deflation of the tyre." SA-067-26713, 06/01/2018.

Although reported as a "potentially serious occurrence", the incident would perhaps be better characterized as a "serious incident avoided by automation" in that had the lightning strike occurred to a manual truck, the consequence could easily have been more serious.

In another case, the incident occurred as a consequence of a "check driver" inadvertently switching an autonomous truck into manual mode.

> "An autonomous mining truck travelling on the haul road in manual mode with a check driver in the cab, mounted a windrow. There were no injuries and the autonomous fleet were suspended. It appears that the check driver who was calibrating the truck inadvertently switched it into manual mode 15 seconds before the truck mounted the windrow" SA-MG-453-16969, 19/06/2014.

This is an example of the general category of "mode error" associated with the introduction of autonomous components to the system.

Other less common incidents included 10 failures of miscellaneous mechanical or electrical components that caused unwanted events such as contact with windrow or emergency braking leading to loss of control.

Loss of traction incidents. A relatively common incident type reported was a loss of traction associated with wet roads (from either rain or recent watering of the roadway). Ten incidents were described in the database, examples include:

> "While approaching the work area of an excavator, an autonomous truck lost traction and braked causing it to slide. The road had been recently watered by a water truck. After losing traction, the autonomous truck breached the lane, attempted to correct its path and maintained its position inside the lane for ~ 45 m. The body boundary then breached the lane again when a stop event was activated on the truck. Upon braking heavily, the truck slid ~ 20 m coming to rest ~ 4 m outside of its planned lane." SA-299-22131, 04/02/2016.
>
> "An autonomous haulage system (AHS) truck was travelling unloaded down a 7 degree curved ramp in an open pit, at 47 km/h, when the rear wheels lost traction against the unsealed road surface. This caused the truck to initiate medium-braking. The truck slowed to 9 km/h, while remaining in its lane, before breaching its programmed path and causing a critical braking response. The truck then slid to the left-hand side and came to rest against a windrow. The total time travelled from the initial loss of traction to rest was 9 seconds and 4 seconds passed from critical braking to rest. An initial investigation indicates the ramp was overwatered. Engineering analysis of the data recovered from the truck showed that the truck operated as designed." SA-861-25701, 25/07/2017.
>
> "An autonomous surface haul truck was travelling down the mine waste ramp at an open pit when it slid and rotated about 90 degrees before rolling onto the cab side. The incident was caused by the truck moving from wet conditions on the ramp to dry as it slid." SA-356-27825, 18/05/2018.

In each of these examples, although control of the autonomous truck was lost and the truck deviated from its intended path (and in one case rolled onto its side) no other vehicles were in the vicinity. In two further examples however, the loss of control resulted in a collision with another autonomous truck.

> "An empty autonomous haul truck (AHT) collided with a loaded AHT at an open pit. The empty AHT breached its lane and entered the path of the loaded AHT. Autonomous operations were suspended and an investigation commenced. It was raining heavily prior to the collision and the empty truck experienced a loss of traction." SA-205-30271, 16/03/2019.

> “Following a rain event at an open pit, an autonomous haul truck made contact with the rear of another autonomous haul truck while on a pit ramp.” SA-275-32600, 16/02/2020.

In both of these cases, the vehicle which lost control made contact with another autonomous vehicle and there was no risk of injury to persons. However, it is possible to imagine more serious consequences arising were an autonomous truck to lose traction whilst in the vicinity of an occupied light vehicle.

It is not known whether the risk of such loss-of-traction events is greater for autonomous trucks than manual operated trucks. However, if it is assumed that the root cause of the loss of traction is a loss of situation awareness (that is, the system is unaware of the roadway state) then it is possible, and perhaps probable, that an experienced and alert human operator with direct sensory perception of the vehicle surroundings would gain awareness of the situation (that is, the roadway conditions and the implications for potential loss of traction) and take appropriate action.

Another autonomous truck to autonomous truck collision that received considerable media attention occurred in February 2019 at Fortescue Metals Group’s Christmas Creek mine. The summary provided by the regulator reads:

> “An autonomous haul truck (AHT) at an open pit reversed and made contact with a parked AHT.” SA-389-29984, 11/2/2019

Additional detail reported[2] suggests

> “The reversing truck stopped when communications were severed. When the wi-fi coverage returned, the truck’s LiDAR (light detection and ranging) technology kicked in, detecting the presence of the truck behind it and remained stationary.… However, the truck then reversed into the stationary machine”.

Although the company’s Chief Executive Officer is quoted as saying, “This was not the result of any failure of the autonomous system”, it is clear that there was an error of some kind involving a Wi-Fi communications error between the truck and control room (Bhattacharya, 2020). The consequences could have been quite different if an occupied light vehicle had been located behind the truck at the time.

Collision / near-miss incidents. The most common type of incident reported involved interactions between an autonomous truck and another vehicle (eg., dozer, water cart, grader, service vehicle or light vehicle) in which the manually operated vehicle encroached into the permission line of the autonomous truck, causing the autonomous truck to brake. Eighteen such incidents were identified, including seven in which the manually operated vehicle then collided with the autonomous truck.

One such incident that occurred in 2014 at BHP’s Jimblebar mine was summarised as:

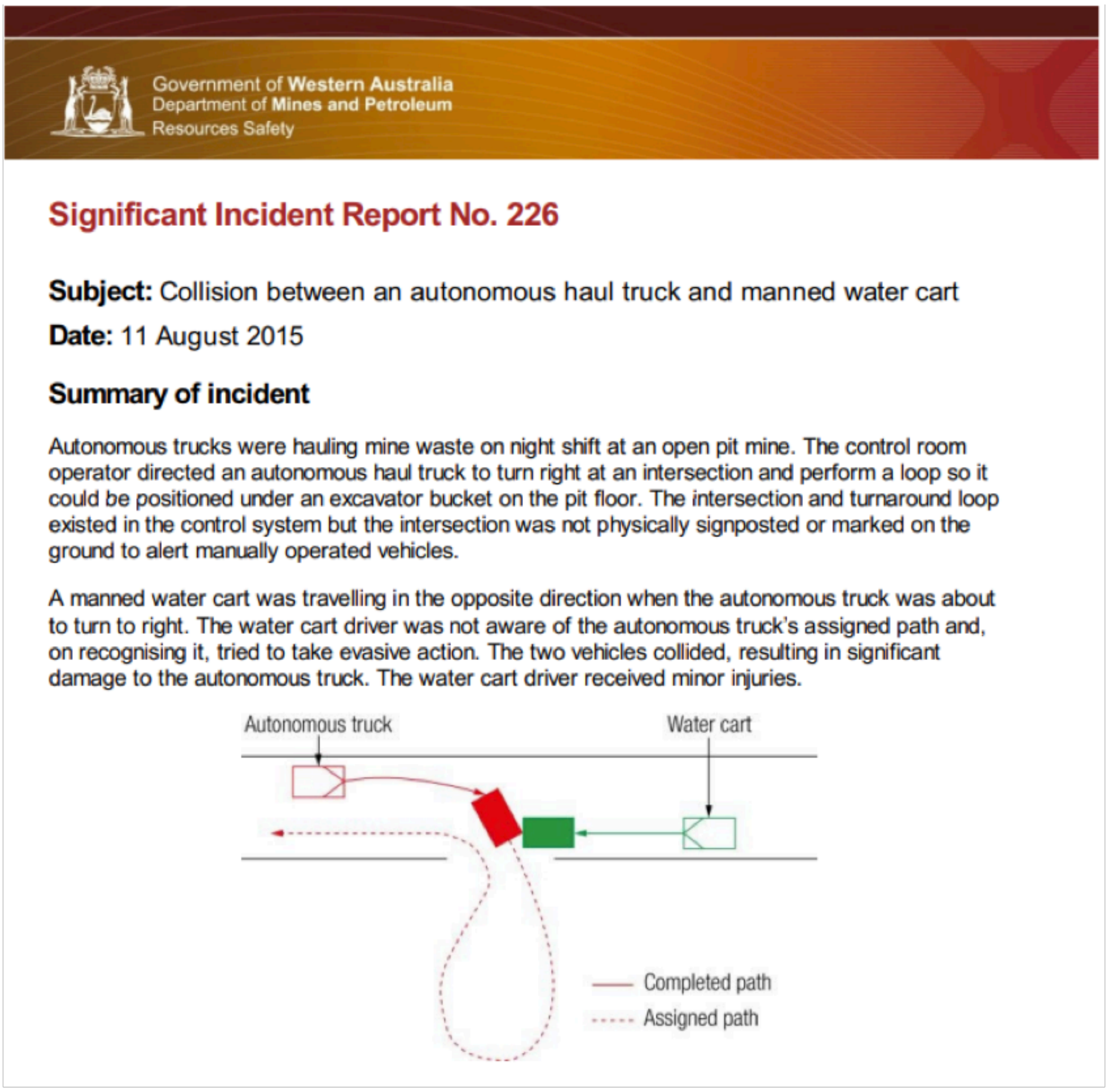
> “An automated haul truck (AHT) turned, under instruction, into the path of a manually operated water cart. The AHT was commencing a loop to position itself beneath the excavator bucket. On realising the intended path of the AHT the water cart operator commenced evasive action. However, the two vehicles collided.” SA-605-17670, 16/8/2014.

Further details of the incident were provided by the regulator in 2015[3] (Figure 2).

---

[2] https://thewest.com.au/business/mining/fortescue-metals-group-auto-haul-truck-crash-christmas-creek-no-failure-of-system-ng-b881104957z

[3] https://www.dmp.wa.gov.au/Documents/Safety/MS_SIR_226_Collision_between_an_autonomous_haul_truck_and_manned_water_cart.pdf


Government of **Western Australia**
Department of **Mines and Petroleum**
Resources Safety

Significant Incident Report No. 226

Subject: Collision between an autonomous haul truck and manned water cart

Date: 11 August 2015

Summary of incident

Autonomous trucks were hauling mine waste on night shift at an open pit mine. The control room operator directed an autonomous haul truck to turn right at an intersection and perform a loop so it could be positioned under an excavator bucket on the pit floor. The intersection and turnaround loop existed in the control system but the intersection was not physically signposted or marked on the ground to alert manually operated vehicles.

A manned water cart was travelling in the opposite direction when the autonomous truck was about to turn to right. The water cart driver was not aware of the autonomous truck's assigned path and, on recognising it, tried to take evasive action. The two vehicles collided, resulting in significant damage to the autonomous truck. The water cart driver received minor injuries.

Figure 2: Description of the collision between a manned water cart and autonomous truck that occurred at BHP's Jimblebar mine on 16/8/2014. (https://www.dmp.wa.gov.au/Documents/Safety/MS_SIR_226_Collision_between_an_autonomous_haul_truck_and_manned_water_cart.pdf)

The direct causes of the incident identified by the regulator were:

- "The travel paths of the autonomous truck and water cart intersected;
- The turnaround loop for the autonomous truck was released for use in the control system but the corresponding intersection was not delineated on the ground, nor its intended use communicated
- On detecting the water cart in its assigned path of travel, the autonomous truck's speed (about 40 km/hr) and response time meant it could not prevent the collision."

Contributory causes identified were:

- "The change management processes for planning and assigning roads in the control system were inadequate;
- *An awareness system was set up in the water cart to allow the driver to monitor the autonomous truck's path. However, at the time of the collision, the water cart driver was not fully aware of the intended path of the autonomous truck*." (*emphasis added*).

This last "contributory cause" identified hints at the initiating event (to use bow-tie analysis terminology) of these incidents — a loss of situation awareness on the part of the operator of the water cart. The note also highlights the importance of the site awareness system provided in manually operated vehicles operated within autonomous zones. Several other incident summaries also note the role of this interface.

> "A collision happened between an autonomous truck and a water cart on a ramp in an open pit. The water cart operator drove onto an active haul road while wetting a section of the pit and *observed an autonomous truck on the screen.* The operator of the water cart determined that there was sufficient room to articulate with the truck approaching and continued in the direction of travel. As the water cart came into the vision of the autonomous truck, the truck applied the brakes and began to slow down. The truck wheels then locked up and contact was made between the two pieces of equipment. The vision of the autonomous truck was impaired as the truck was approaching from the offside of the water cart." SA-992-22337, 05/03/2016. (*emphasis added*).
>
> "A water cart entered an intersection in the path of an autonomous haul truck during night shift at an open pit. The operator braked and came to a stop three metres from the truck. A light tower was facing the windscreen of the water cart impeding the operator's view of the intersection. *The operator used the mapping display to check on the location of autonomous vehicles and misinterpreted the location of the truck*." SA-019-30692, 03/06/2019 (*emphasis added*).
>
> "As the driver of a light vehicle (LV) approached an intersection on a haul road he observed the flashing light and clearance light of an autonomous haul truck (AHT). *The driver of the LV looked at the screen to view the permission line of the AHT but was unable to view it and decided to zoom out on the screen.* At that point the LV driver saw the headlights of the AHT turn towards him as the two vehicles entered the intersection. The driver of the LV applied the brakes and stopped and the AHT's safety systems were activated to "exception" mode (where all brakes are applied) and the vehicle stopped. The two vehicles came to rest 5-10 m apart." SA-380-18526, 15/01/2015. (*emphasis added*).
>
> "At a Y-intersection in an open pit a light vehicle (LV) avoidance boundary intersected the lane of an empty autonomous dump truck. The crossed path initiated a critical stop resulting in a near miss, with the vehicles coming to rest ~ 4.0 m apart. … *An investigation into the incident found that the LV driver lost situational awareness, having been distracted by focusing on the site awareness screen* located between the front seats of the vehicle out of the field of view of the driver. The Y-intersection was found to be in breach of the traffic management plan (TMP) for the site and was in the process of being turned into a T-intersection." (*emphasis added*)

These incidents highlight the importance of the site awareness system in assisting operators of manually operated equipment within the autonomous zone maintain situation awareness. In turn this directs attention to the design of the interfaces by which such systems provide information to the human operator working in close proximity to the autonomous trucks.

However, one of the "near-miss" collision incident reports hints at an initiating event other than loss of situation awareness.

> "Replays from an autonomous haul truck (AHT) showed a potentially serious occurrence at an open pit mine. The AHT was approaching an intersection on a haul road near the ROM, and had its permission line out, indicating its intention to turn right. As it slowed down and started turning, a light vehicle approached from the opposite direction and continued entering the intersection. The AHT identified the collision risk, applied its brakes and came to a stop. The light vehicle did not stop, but continued through the intersection, passing less than 10 m from the AHT. The driver of the light vehicle failed to give way, as per pit permit requirements, and did not stop, call mayday or report the incident to their supervisor." SA-520-26849, 09/01/2018.

It is hard to imagine the operator of a light vehicle failing to notice passing less than 10m away from a haul truck. While this incident may have been a particularly egregious example of loss of situation awareness, it is more likely that this is an example of the general potential for "over trust" in automation to lead to behavioral changes that degrade the safety of the system — that is, the light vehicle operator had such trust that the autonomous truck would stop that they deliberately drove through the intersection in front of the truck. Combining this situation with a loss-of-traction event yields a plausible fatality scenario.

Unwanted outcomes arising in the absence of system failure. Two final summaries of automation incidents deserve comment as examples of how unwanted outcomes can arise in complex systems in the absence of failure of any system component. The first resulted in a truck-to-truck collision.

> "An autonomous haul truck stopped on an open pit ramp. A single lane was created for other autonomous trucks to pass the truck. A worker arrived to manually recover the truck. It was started and driven up the ramp into the path of a second truck as it was passing. The trucks made contact, stopping on the ramp. … The proximity detection/site awareness system was not fully operational on the first truck when it travelled into the single passing lane." SA-051-28892, 03/10/2018.

In this case, when the operator re-started the autonomous truck to drive it manually, there was a delay before the truck's site awareness system was actively broadcasting it's position, and hence the approaching autonomous truck was unaware of the first truck's location. No feedback was provided to the driver that this was the case and the driver had no visibility of the passing autonomous truck approaching from behind. This combination of circumstances resulted in the autonomous truck being unable to stop when the manually operated truck was driven into it's path (the laws of physics still apply). All system components functioned as intended, however the collision still occurred.

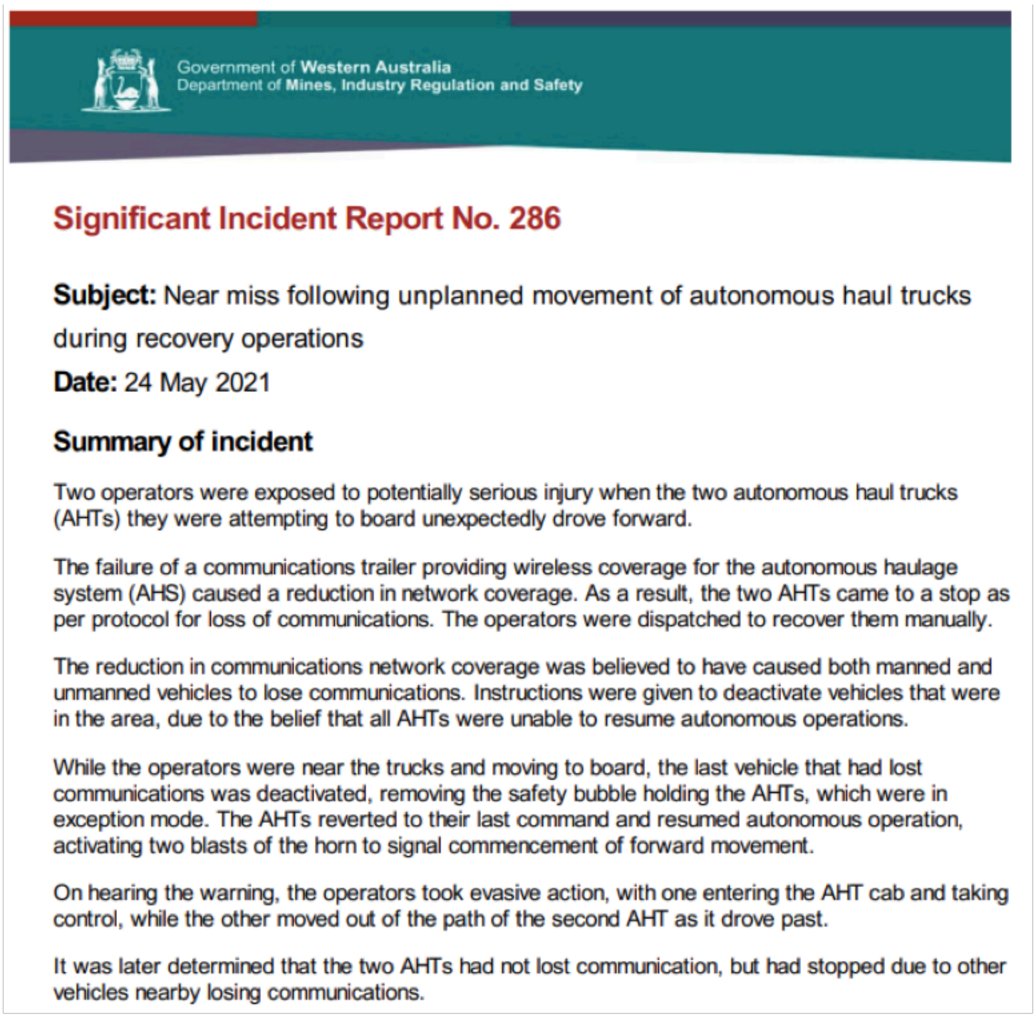
The final incident that occurred in 2019 resulted in an unusual interaction between two pedestrians and unexpected movement of two autonomous haul trucks that had serious potential consequences:

"After two autonomous haul trucks (AHTs) at an open pit lost communication, two operators were tasked with relocating the vehicles. As the first driver entered the cab of an AHT, the vehicle moved forward while the operator applied the brake and switched to manual mode. As the second operator was about to board the other AHT, its horn sounded and the vehicle moved forwards, with the operator stepping out of the way." SA-743-32237, 29/12/2019.

The regulator provided additional information in 2021[4] (Figure 3).

---

[4] https://www.dmp.wa.gov.au/Documents/Safety/MSH_SIR_286.pdf



Government of **Western Australia**
Department of **Mines, Industry Regulation and Safety**

Significant Incident Report No. 286

Subject: Near miss following unplanned movement of autonomous haul trucks during recovery operations

Date: 24 May 2021

Summary of incident

Two operators were exposed to potentially serious injury when the two autonomous haul trucks (AHTs) they were attempting to board unexpectedly drove forward.

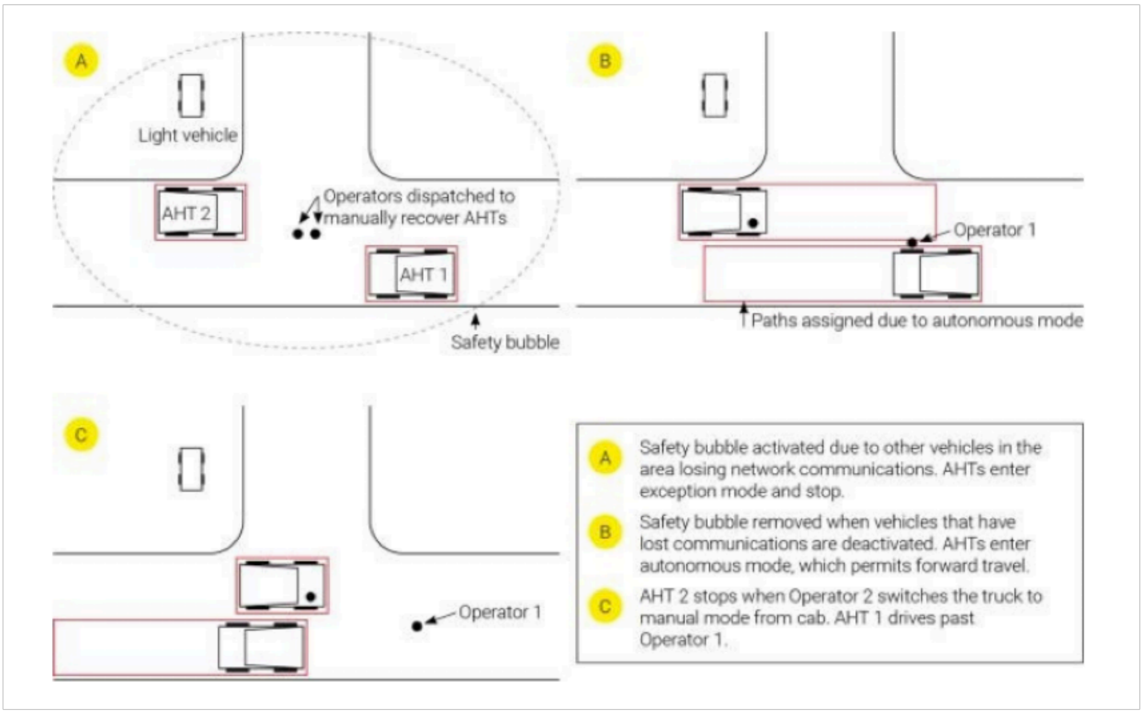
The failure of a communications trailer providing wireless coverage for the autonomous haulage system (AHS) caused a reduction in network coverage. As a result, the two AHTs came to a stop as per protocol for loss of communications. The operators were dispatched to recover them manually.

The reduction in communications network coverage was believed to have caused both manned and unmanned vehicles to lose communications. Instructions were given to deactivate vehicles that were in the area, due to the belief that all AHTs were unable to resume autonomous operations.

While the operators were near the trucks and moving to board, the last vehicle that had lost communications was deactivated, removing the safety bubble holding the AHTs, which were in exception mode. The AHTs reverted to their last command and resumed autonomous operation, activating two blasts of the horn to signal commencement of forward movement.

On hearing the warning, the operators took evasive action, with one entering the AHT cab and taking control, while the other moved out of the path of the second AHT as it drove past.

It was later determined that the two AHTs had not lost communication, but had stopped due to other vehicles nearby losing communications.



A Safety bubble activated due to other vehicles in the area losing network communications. AHTs enter exception mode and stop.

B Safety bubble removed when vehicles that have lost communications are deactivated. AHTs enter autonomous mode, which permits forward travel.

C AHT 2 stops when Operator 2 switches the truck to manual mode from cab. AHT 1 drives past Operator 1.

Figure 3: Description of unintended autonomous truck movements in proximity to pedestrians that occurred 29/12/2019. (https://www.dmp.wa.gov.au/Documents/Safety/MSH_SIR_286.pdf)

The direct causes identified were:

> "Operators attempted to board the AHTs while they were not under their control
>
> The operators did not identify that the AHTs were in exception mode when attempting to board.
>
> Once the light vehicles in the area were deactivated, which removed the projected safety bubble, the AHTs reverted from exception to autonomous mode allowing them to resume operations."

Contributory causes were listed as:

> "AHTs were in exception mode and not suspended (unsafe mode to approach). Lack of understanding or clarity regarding the actions of the AHTs in various modes of operation.
>
> Limited redundancy in communications network utilised by the Autonomous Haulage System (AHS). Ability for personnel to override system functions that are designed as critical safety controls.
>
> Operators did not observe the AHTs status mode indicator lights.
>
> Previous AHS communication issues may have desensitised the operators to potential hazards.
>
> AHTs did not detect a person about to board."

Again, the loss of control of the situation occurred despite all systems functioning as designed. In both cases a lack of feedback to the people in the system about the state of the autonomous components, or a lack of understanding of the information provided, contributed to the event. These examples both illustrate why conventional failure-based risk analysis methods are insufficient to understand the risks associated with complex systems that include autonomous components. Additional analysis techniques such as Strategies Analysis for Enhancing Resilience (SAfER) & System-Theoretic Process Analysis (STPA) are also required (Hassall et al., 2022).

Jimblebar automated truck incidents

Pascoe et al (2022b) provide an analysis of incidents associated with haul trucks; both manually operated and automated, recorded by BHP's Jimblebar mine in Western Australia for four years that spanned the introduction of autonomous haulage to the site (FY2014-FY2018). These incidents include a larger range of incidents than those required to be reported to the regulator. The overall incident rate per million hours given declined by more than 90% over the period from 590 incidents/million hours in to 51 incidents/million hours in FY18 (Figure 4).

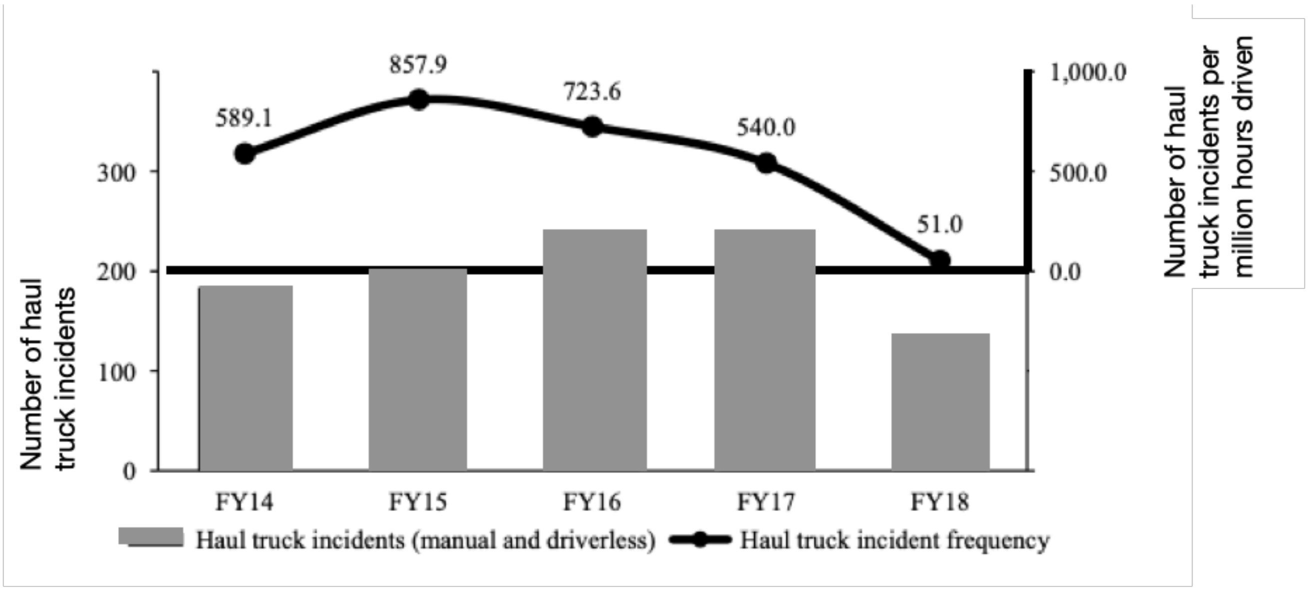


Figure 4: Haul truck incidents at Jimblebar FY14-FY18 (adapted from Pascoe et al., 2022b)

As well as a markedly reduced rate of incidents, the nature of the incidents changed. As noted in the previous analysis of incidents reported to the regulator, loss-of traction events associated with wet roads accounted for 27% of autonomous truck incidents identified on the site. While loss-of-traction events did occur with manual trucks:

> "the incident pathways in driverless were novel and more frequent. Lane breaches were caused by communication losses, speed zones or wet road conditions. Loss of network immediately stopped trucks and frequently caused lane breaches. … Driverless trucks are unable to 'see' wet roads. Instead, trucks relied upon traction and speed zones to be put in place by humans. Road objects that were suddenly detected caused a number of trucks to slide out of lane. Since the technology is yet to distinguish between objects, trucks cannot determine the difference between tumble weed, centre dividers and non-site aware vehicles." (Pascoe et al, 2022b, p. 20).

The contrast with the ability of drivers to adapt to wet roads was noted, along with an important comment highlighting the importance of communication between truck drivers.

> "wet roads existed in manual and driverless operations. However, both systems managed them in vastly different ways. A driver could easily spot increases in rain fall, adjusting their speed and drive to conditions. *Truck drivers also spoke amongst themselves to be mindful of certain road conditions on the circuit.* Driverless trucks, on the other hand, relied upon traction controls and system users to install speed zones on impacted areas. The operation's 'eyes and ears' were effectively replaced with 'satellites and sensors'." (Pascoe et al, 2022b, p. 22, *emphasis added*).

Some errors were still reported because human intervention was still required, and human errors can still be made. For example:

> "Although automation successfully prevented trucks from entering closed Active Mining Areas, the system relied heavily on LV's to virtually lock the area. Driverless trucks drove into Active Mining Areas where light vehicles forgot to lock or engage the button effectively (Pascoe et al, 2022b, p. 20)

It was also noted that interactions between manually operated equipment and autonomous trucks still occurred, and in particular, loss of situation awareness was noted while dozers cleaned up around the excavator:

> "Clean-up machines recorded the highest number of incidents. Dynamic lanes are able to flip from one side of the excavator to another. Dozer operators not watching in-cab displays were surprised by lanes generated into their work area. Trucks effectively 'sneak up [on] them'."(Pascoe et al, 2022b, p. 21).

Damage to truck trays still occurred as a consequence of excavator strikes; and tyre separation and equipment breakdowns still occurred.

Vehicles that are not fitted with the autonomous system site awareness technology are permitted in the autonomous area if accompanied by an escort vehicle that is site aware. It was noted that a breakdown to an escort vehicle on one occasion left a non-site aware vehicle with fewer layers of protection.

One change to the autonomous system is that truck refuelling is no longer undertaken by the driver. Other personal injury risks associated with truck driver are eliminated including risks associated with access and egress, exposure to whole body vibration and other musculoskeletal risk factors, as well as respiratory hazards.

More recent information provided by BHP (Figure 5) indicates that the safety improvements continued in subsequent years (Craig, 2022). A 65% reduction in events with fatal potential across the Western Australian Iron Ore division was reported from FY18 to FY22 and this was attributed in part to the introduction of technology and automation, and in particular to the autonomous haulage introduced at Jimblebar.

"The continued roll-out of technology and automation across our business is also having a positive impact on our safety, including the Surface Mobile Equipment anti-collision program.   We know from the safety performance at Jimblebar, autonomous trucks have resulted in 75% fewer collision incidents than at our non-autonomous mines." (Craig, 2022, p. 10).

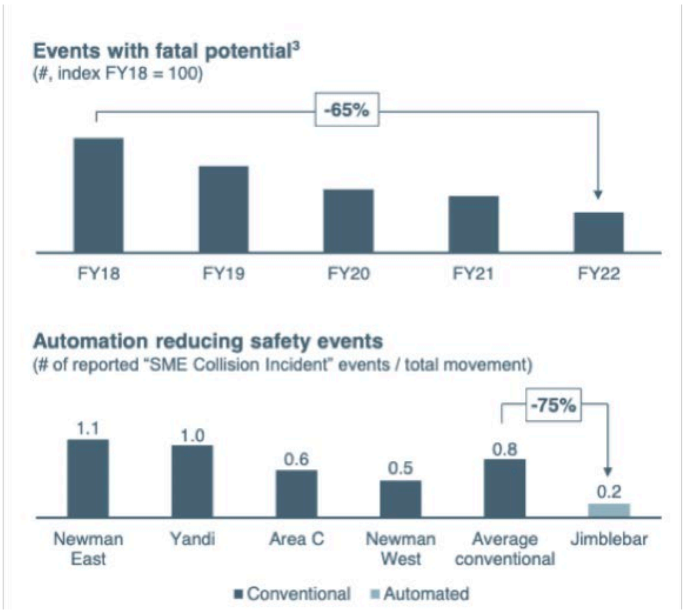


Figure 5: Safety improvements at BHP Western Australian Iron Ore sites associated with the introduction of autonomous trucks. (Craig, 2022).

Rio Tinto - Collision near-miss comparison

Rio Tinto have provided a comparison of the rate of collision near-misses between manual and autonomous surface operations, classified by remote object (Figure 6). About 50% of all Rio Tinto surface sites run autonomous haulage, however the majority of the autonomous sites are Australian (about 82% of the Western Australian Rio Tinto Iron Ore truck fleet are autonomous). It may be that there are systematic differences between Rio Tinto sites in Australia and elsewhere other than autonomy, however the rate of collision near misses involving trucks was an order of magnitude lower at the autonomous sites than the manual sites — approximately 0.27 near misses per million truck hours at autonomous sites vs 2.76 near misses per million truck hours at manual sites.

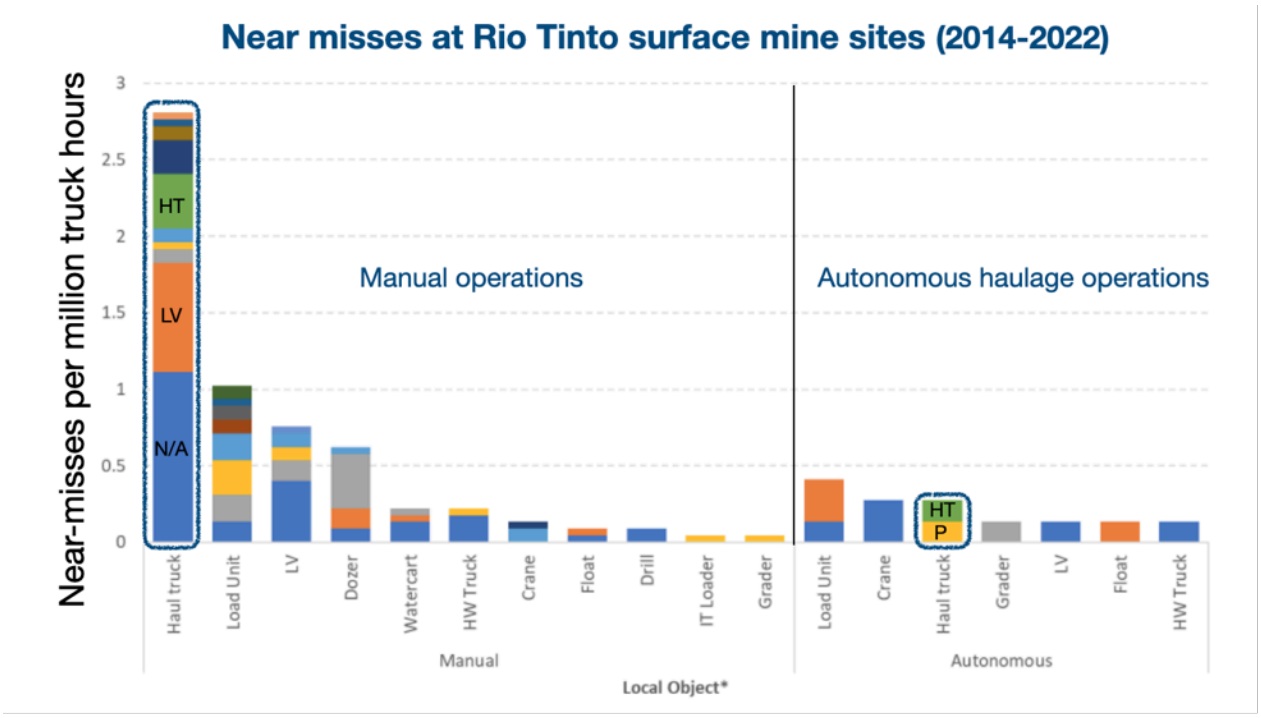


Figure 6: Collision near-misses at Rio Tinto surface sites comparing manual and autonomous haulage sites. (Fouche, 2023).

Semi-automated Dozer collision (Wilpinjong, NSW)

A collision between a semi-automated dozer and an excavator occurred in New South Wales, Australia at Peabody Energy's Wilpinjong Coal Mine on May 27, 2019. The NSW Resources Regulator has provided an investigation report (NSW Resources Regulator, 2019) as well as simulated reconstruction (Figure 7).

Figure 7: Overview of the collision between a semi-autonomous dozer (DZ2003) and excavator that occurred at Wilpinjong mine in 2019. (https://www.youtube.com/watch?v=zLqxdVa66qY).

Semi-autonomous (SATS) dozers were being utilized to undertake bulk push operations. This technique requires an excavator to clean the rear bench material to where the dozers reverse before commencing a push. The material is used to create a windrow across the back of the dozer push area. A procedural control was in place in that a manually operated machine should not operate in the active dozer slot. At the time of the incident, no collision avoidance systems were operational.

Three semi-autonomous dozers were being supervised from the remote operator station shown in the foreground of Figure 7 by a trainee operator under instruction. Each dozer is fitted with four video cameras and these video feeds are displayed at the operator workstation (Figure 8). The workstation includes teleoperation controls. In semi-autonomous mode, the operator allocates a dozer to a slot and conducts the first push of the mission via teleoperation mode. The dozer then continues to operate in the same slot autonomously until either the mission is completed or until 12 passes have been conducted and the operator must reconnect with the dozer.

According to the investigation report:

> "At 1.30pm, the excavator operator resumed work within the SATS avoidance zone from the north, travelling towards the south. As the edge bund was constructed using material from the highwall face, some loose material was hanging up across the face. The operator used the excavator to scale the loose material from the face, as he travelled towards the southern section of the SATS avoidance zone.
>
> As the excavator had previously scaled and cleaned up the northern area, a windrow had been built between the rear bench and the SATS dozer push slots. This resulted in the excavator working between the highwall face and the windrow. As loose material was scaled down, it was

> added to the windrow. The task progressed towards the south until the excavator travelled to the end of the windrow and was positioned adjacent to the rear of slot 16.
>
> At this point, dozer DZ2003 was operating in slot 16, while dozer DZ2002 and dozer DZ2010 were working in adjacent slots in the southern section of the avoidance zone about 50 metres away. Dozer DZ2003 had been operating semi-autonomously for some time. Immediately before the collision, the SATS operator had selected and was observing dozer DZ2002 until dozer DZ2010 ceased pushing. The SATS operator switched to this machine and started fault-finding.
>
> Dozer DZ2003 had completed a push and was reversing towards the rear of slot 16 to start the next push. At this time the excavator proceeded past the windrow, into slot 16. About 1.40pm, dozer DZ2003 hit the rear of the excavator. When initial contact was made, the excavator was pushed about 1.5 metres sideways, into the base of the highwall. The excavator then stopped sliding and dozer DZ2003 continued to tram in reverse, colliding with the excavator multiple times trying to reach its programmed GPS coordinates.
>
> Dozer DZ2003 eventually lost traction and after five seconds, the control system faulted and stopped tramming. From the initial contact to dozer DZ2003 stopping was about 14 seconds. The excavator had some damage however the operator was uninjured." (NSW Resources Regulator, 2019)

When a dozer is selected by the supervisor, a screen in front of the operator displays the four cameras corresponding to the dozer that is the focus of the operator's attention. A small side panel also shows two camera views for each of the other three dozers. Figure 8B illustrates the supervisor's view immediately prior to a collision. While information was available to the supervisor, it was not provided in a way that facilitated maintenance of accurate situation awareness and it is understandable that the collision was not predicted by the supervisor who was focussed on fault-finding on DZ2010.

Figure 8: Remote operator station provided to the supervisor of three semi-autonomous dozers (A - top left); video images available (B - bottom) immediately prior to the collision between dozer 2003 and an excavator (C - top right). (NSW Resources Regulator, 2019).

USA data

A set of MSHA data was obtained that included injuries and near misses comprising 91,957 total incidents in the US from 2010-2020. A natural language-type word search and categorizing analysis of those data identified 2018 cases that were noted as involving use of machines. Of those 2018 cases, 76 cases involved automation or autonomous equipment and six cases noting the use of robots. However, a closer examination revealed that not all of the 76 cases were actually related to automation; and none involved automated mining equipment. Most of the 76 cases do, however, involve either an unintended physical switching from manual to automatic (unintentionally bumping a controller) or vice versa or an intended but mistaken switch due to the operator or maintenance technician not knowing which mode was engaged. The equipment involved automated palletizers, automated equipment doors and automated conveyors/rollers. For example:

> "Employee was welding on a pipe in the East Ridge Floatation. He was unaware his automatic welding shield had been adjusted by another employee prior to his use; he sustained a flash burn to both eyes"
>
> "Employee was riding in mantrip trailer. Another employee activated the automatic ventilation doors and then let go of the control switch box. The box swung back slightly and hit the injured employee on the cheek"

The incidents involved broken arms and legs in some cases. This is an indication of at least one of the safety-related problems that will continue to be a part of the transition from fully manual to fully autonomous.

Global mining industry experiences of automation

Safety and health benefits of implementing automated mining equipment were universally reported, regardless of the mine or equipment type. Productivity improvements were also very commonly reported, particularly linked to increased equipment utilization. While people have been required to change roles, the introduction of automation does not appear to be commonly associated with a reduction in overall employee numbers and companies generally reported that no redundancies were associated with the introduction of automated mining equipment.

Variability was reported in the response of staff to automation. There was a general perception that younger staff are more accepting of change, however some experienced operators enthusiastically contributed good ideas for improvement during implementation of automation. At one site there appeared to be considerable cultural resistance to the implementation of automation; and at another mine, a lack of enthusiasm at the corporate level than impeded implementation of automation was described.

The number of manual equipment operators may decrease, however the need for specialist maintenance staff (e.g., IT, electrical, sensors, and software) increases with the implementation of automation. Automation has potential to increase industry employment overall by allowing otherwise unviable mines to continue, or to commence, operation. This will be particularly important given the significant demand for minerals to meet decarbonisation targets, the declining grades of available ores, and increasing deposit depths (International Energy Agency, 2022).

Indeed, for many global mining companies a shortage of workers is looming as a serious challenge—in part because young workers are not attracted to a career in mining (PWC, 2023). Automation is seen as an important means of increasing the "attractiveness" of mining as a desirable industry in which to be employed (cf. Lööw et al., 2018). It was noted that future miners will require higher education levels.

Some miners reported being thrilled with now being "so much more than just miners". In addition to the attractiveness of working in a control room as opposed to underground, it was reported that the control centers can be and are being strategically located in more liveable cities instead of relocating miners to the remote corners of the world where many mines are located. This opens the door to many more potential employees. However, some also report being concerned that their work is more sedentary.

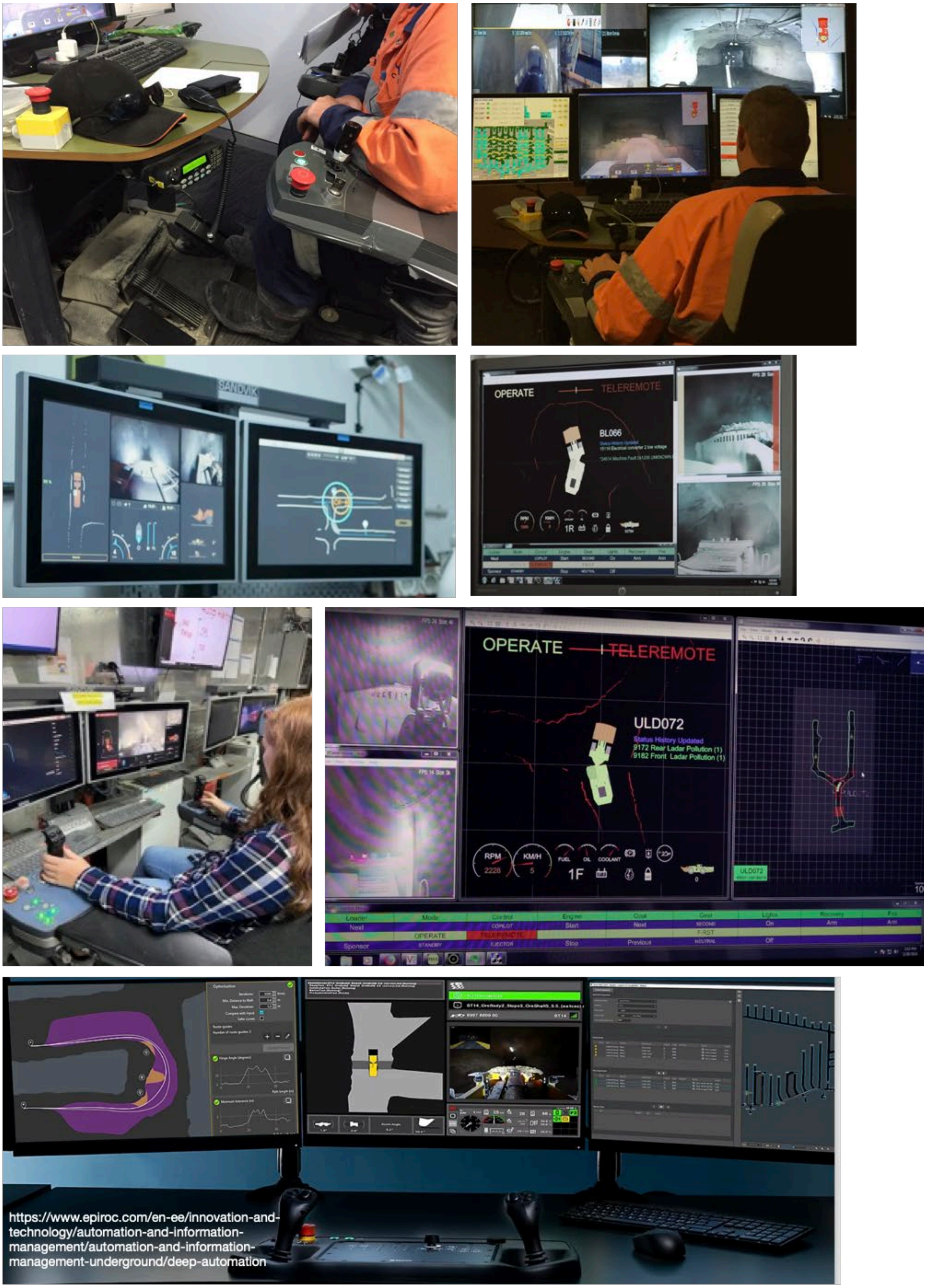
A wide range of issues associated with the introduction of automation were noted through both visits and discussions with key informants. It was noted that the introduction of an autonomous system will impact everyone on the mine and some issues were highlighted, for example: interoperability concerns; vulnerability to communication failures; isolation procedures; the impact of automation on situation awareness; and the importance of interface design; are common across equipment and sites. Other issues are specific to the equipment type. Virtual reality/simulation was consistently identified as providing opportunities for training and competency assessment. Related, and additional, challenges are associated with moving to battery and/or hydrogen energy, although these issues are beyond the scope of this investigation.

Underground mining equipment

Autonomous drills, trains, and LHDs were operated at the underground metal mining sites visited, and an automated longwall was in use at an underground coal mine visited. The motivations for the automation of underground equipment include safety concerns, and particularly exposure to seismic events as mining is undertaken at greater depths and/or in more seismically active areas. Increased depths are also associated with greater heat and longer travel times.

Load-Haul-Dump

Semi-automated LHDs have been installed at more than 50 mines globally since 2006. Operators located in a control room load the LHD bucket using via tele-operated control. The loader is then switched to autonomous mode to travel to the dump where the load is dumped autonomously. The loader then autonomously returns to the next load point selected by the operator. Operators may be responsible for supervising multiple loaders. A range of interfaces are provided to allow the remote operator to maintain situation awareness and remotely control the loading phase (Figure 9).



https://www.epiroc.com/en-ee/innovation-and-technology/automation-and-information-management/automation-and-information-management-underground/deep-automation

Figure 9: Semi-autonomous underground LHD operator interfaces.

Removing operators from the hazards associated with manual loader operation brings considerable safety and health benefits and no reports of injuries associated with this equipment have been identified. This is likely to be, in part at least, because current practice is to isolate all other equipment and pedestrians from the zones in which autonomous LHDs operate. However, incidents have occurred where automated equipment has been activated in an isolated autonomous area with multiple working faces while persons were located at another face.

Remote-control loaded buckets are, on average, loaded with smaller amounts of material than manually loaded buckets. However, overall productivity is higher because increased equipment utilization arises as a consequence of being able to continue operation through blasting and shift changes. It was suggested that the LHD supervisors located remotely from the loaders do not feel the quality of the roadway and may allow the loaders to drive at speeds that increase maintenance requirements.

The location of the control workstation for the semi-autonomous LHDs varies across sites. One site located the LHD control room underground and this was seen as beneficial for maintaining communication with other staff underground. Other sites have chosen to locate the LHD control room on the surface of the mine to reduce underground travel time, or in a remote operations center in a location at some distance from the mine. At another mine, semi-autonomous LHD supervision was undertaken both in a control room on the surface of the remote mine and in a control room located in the company’s city office. Locating control rooms in centralised locations has potential to attract mine-workers who were unable or unwilling to undertake a Fly-In-Fly-Out roster.

However, the design of some mines may not lend themselves to the currently available technology. For example, one mine visited that had attempted implementation of semi-autonomous loaders stopped the project before its completion. The main entry in the mine is of a spiral design structure with ramps at all levels branching off from the spiral structured main entry. This design is not conducive to automated operations. It was difficult for the loaders to make the tight turns necessary to operate and move to required locations. Manual operators were willing to force the loaders to make the turn (sometimes even striking the ribs with the machine). The operating cushion for an automated loader did not allow this and the machines would stop when the machine drove too close the rib to avoid striking the rib. Even where the mine design is conducive to automation, the integration of semi-autonomous loaders into existing production systems is not straight forward and difficulties typically arise in maintaining production during the transition. Not every site that implemented semi-autonomous LHDs has persisted with the technology and some sites have taken several attempts before being successful. It was suggested that the implementation of LHD automation required a strong mandate from the highest levels of the company to be successful in the face of inevitable, if temporary, production declines during implementation.

This observation was consistent with the findings of a previous case study of the successful implementation of semi-autonomous loaders at CMOC NorthParkes (on the site’s third attempt). The strategies for successful automation implementation included: involving all people who will be impacted; encouraging constant communication between operators and designers; provide operators with essential information; avoid providing non-essential information; provide the operators with flexibility; empower operators to take action; and taking advantage of the new possibilities provided by automation (Burgess-Limerick et al, 2017).

One issue identified at NorthParkes during the initial preparation for the transition to autonomous LHDs was that all underground tasks would be affected by the change. For example, at shift change the continued operation of LHDs from the surface enables production to continue, removing time pressure and allowing greater time for shift handover. However, it was also identified that access to, or through, sections of the mine where autonomous loading was in operation would be prevented and this impacted on the performance of many other tasks.

Constant communication between operators and designers throughout the implementation and subsequent operation of the semi-autonomous loaders was critical in developing and refining the control room user interface. Continuous presence of manufacturer expertise on-site allowed a rapid feedback loop with designers.

Providing operators with opportunities to suggest modifications to the system was a key feature in the success of the implementation. Operators continually updated a list of issues, and a ‘wish list’ of improvements, which were fed back to the system designers, and many changes resulted. For example, equipment damage was occurring because the loader was hitting the walls of the draw point while under manual control. Using the laser scanners already in place for autonomous navigation to detect the proximity of the walls was suggested during manual operation and to convey this information to the operators through changes in colour of the scanning information provided on the teleoperation assist window. This information was also used to automatically apply the brakes if necessary to prevent collision with the walls.

Similarly, wheel spin caused damage to the LHD wheels but was hard for operators to detect while loading remotely. A wheel-slip detection sensor was added and an indication of wheel slip provided to the operator through a change in colour of the schematic loader wheels in the teleoperation assist window. In both cases the presentation of relevant information to the operators in a meaningful way ensured the information could be used effectively to reduce equipment damage.

Relevant information is also conveyed inadvertently, rather than by design. One operator explained that it can be difficult to gauge when the bucket has been lowered sufficiently to the ground in preparation for loading, however if too much pressure is placed on the ground by the bucket, the front wheels will raise and the wheels slip. The operator noted that the camera shake, which could be seen on the video feed when the bucket was lowered, was a useful cue.

Conversely, another change made during system implementation was to reduce the number of fault alarms presented to the operator. Many of these alarms, while relevant to an engineer during commissioning, were not relevant to the day-to-day operation of the LHD. As well as being a nuisance to operators because each message required acknowledgement, becoming habituated to frequent non-essential error messages was reported to have led on at least one occasion to an operator failing to react to a critical error, with potentially serious consequences. Providing flexibility in information provision was another strategy employed. The LHDs are fitted with a microphone and the audio is available to the operators, however it was found that this information was not wanted by the operators and the audio is left off because the nuisance value of the noise outweighs the benefit of any relevant information conveyed.

Many details of the automation implementation were left to production crews to determine. For example, in the transition to autonomous loading, some crews decided that all members of the crew would be trained for autonomous control, while other crews chose to have specialist autonomous operators. The number of LHDs for which an operator should have responsibility was also determined by the crews. While four loaders can be controlled by one person, the cognitive load was overly fatiguing and three was determined to be optimal. During operation, some crews choose to allocate three LHDs to be controlled by each operator, while other crews allowed more flexibility, with all loaders able to be controlled by any of the three operators on shift at any one time.

Allowing crews to choose different strategies provides opportunity to evaluate different options, and comparisons between operator and crew productivity can be used to fine-tune operator strategies and identify aspects of operator behavior that lead to improved productivity. Production crews have also taken action without involving the system designers. One issue encountered was that the cameras and scanners were accumulating dust which was causing the automation to fail. While the system designers were exploring options for on-board cleaning mechanisms, the crews devised a means of dumping water on the camera and scanners when required. Making all aspects of the control system as flexible as possible and giving operators maximum control over the automation increases the opportunities that operators have to adapt to new situations.

The implementation of autonomous loading has also had unanticipated consequences for future process improvements. The ability to more flexibly execute different draw point extraction patterns, and modify these extraction patterns, prompted the development of optimization software to determine in real-time the optimal pattern of extraction. This is itself a form of automation which will provide assistance to the shift-boss in maintaining situation awareness of the extraction and aid decision-making.

There were differences between sites in whether a mixed fleet of manual and semi-autonomous LHDs are employed, or whether an exclusively autonomous fleet is operated. A mixed fleet has the advantage that manual LHD operators can be trained to operate semi-autonomous LHDs as well, as occurs at LKAB’s Kiirunavaara mine in Sweden (Tariq et al., 2023); while an exclusively semi-autonomous LHD fleet such as operated at CMOC NorthParkes will eventually require methods of training operators who have never operated a manual loader. The use of virtual reality training is a logical solution, however this may be less of an issue when the loading phase is also automated and the LHD are fully autonomous.

Drills

The sites visited were at various stages of the move to autonomous drills. One site visited was at the beginning of the transition - drillers programmed the drill pattern, depths and angles in the cab (Figure 10), then set the machine drilling and was free to move to repeat the process at another.

At another site, the drills were operated semi-autonomously from an underground control control room. The safety benefits of remote supervision was highlighted by an anecdote from the site about a rock-fall that buried and destroyed a drill while it was operating autonomously - a likely fatality avoided by automation.

However, the supervisor of the autonomous face drill located in an underground control room does not have access to direct perceptual cues, including auditory cues that provide information about ground conditions encountered such as cavities and clay. It was reported that automation has lead to a loss of manual drilling skills. This is problematic because the autonomous drills currently in use cannot cope with all ground conditions and manual operation is still required in difficult conditions (an example of clumsy automation in which easy tasks are automated while complex tasks are left for a human operator [Wiener, 1989]). In one underground metal mine, even though the drill is automated and programmed to drill the whole face pattern, the operator remains underground with the machine to cope with this unpredictable ground condition problem. It was suggested that the designers of the automated drill rigs needed to spend more time on site understanding the requirements of the task. In other words — that a more human-centered design process was required. Drill bit change was still undertaken manually and as was tramming between locations. Automation of these function is required for full automation.

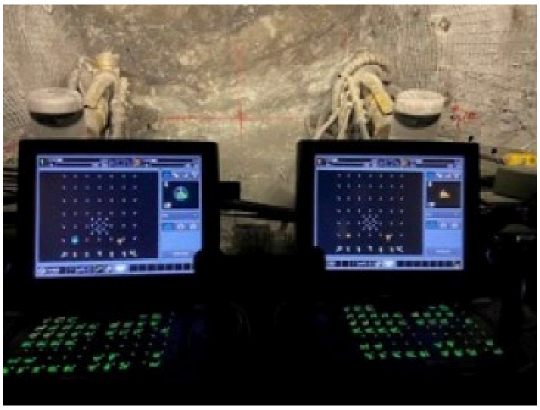


Figure 10: In-cab interface for programming drill patterns

Although currently not commercially available, Sandvik has demonstrated the "AutoMine Concept Underground Drill", a fully autonomous cableless twin-boom development drill rig including autonomous tramming, autonomous drill bit change, and "RockPulse — Online rock sensing for optimised drilling" (Butcher, 2023[5]) that may meet these needs, if drilling can be achieved in the complete range of ground conditions encountered (Figure 11).

---

[5] www.youtube.com/watch?v=uTWQt9hCJj4

Figure 11: Fully autonomous Concept underground drill including autonomous tramming and drill-bit change (Butcher, 2023).

Production control system

When the control room for automated train, crusher, and hoisting system at an underground metal mine was moved to the surface there was initial reluctance from the operators, however the convenience has won them over. Some disadvantages have been reported, particularly the loss of personal interaction with underground staff such as maintenance crews, with a loss of understanding of the day-to-day links between control room decisions and maintenance requirements. It was noted that working in the control room is very sedentary and that this has had health impacts on the control room operators. It was also noted that a new human-machine interface associated with a change of control systems was a retrograde step and that operator feedback had been ignored by system designers.

Although the system is automated, errors still occur. For example, to "do a number 22" is an expression used in the control room to mean filling more than the 21 wagons on the train. It is also important not to overload the capacity of the vertical hoist—this has occurred, with serious consequences, although no people were in the area at the time. Such errors are more likely to be made by inexperienced control room operators and are associated with a loss of situation awareness. It was noted that new operators need understanding of the underground equipment and environment that is difficult to gain from working on the surface, and that there may be potential problems ahead when current staff retire. It was suggested that while virtual reality training may be effective, the loss of expertise could also be compensated by improved systems/sensors and interfaces that allow operators on the surface to maintain accurate situation awareness.

Additional automation of underground equipment was seen as desirable, including rock breakers, rock reinforcement and scaling.

Longwall

Working at the longwall of an underground coal mine is associated with a range of safety hazards, most notably rock falls, outbursts or the ignition of methane. A recent incident is described below:

"At the time of the serious accident at Grosvenor mine on 6 May 2020, there were five coal mine workers at the tailgate end of the longwall, between shields #100 and #133. Three of the workers were as far as 260 metres from the maingate. They were 390 metres underground. … Unquestionably, the event was terrifying. There were two forceful pressure waves 15 seconds apart, sufficient to knock a person over. … in the course of the tumult, the power dropped and there was a brief but intense methane explosion at the tailgate end of the longwall. Each of the five workers was seriously burned. …" (Martin & Clough, 2021, Foreword).

Health hazards, and particularly exposure to respirable dust and noise, are also associated with working in the area (Bauer et al., 2006; Brodny & Tutak, 2018). Automation of the longwall has great potential to reduce the exposure of miners to these hazards. Current technology has removed two miners to a surface control room. While the majority remain underground, they work in less hazardous locations.

Remote guidance technology continuously steers the longwall, automatically plotting its position in three dimensions and allowing real-time monitoring of progress. According to the CSIRO, longwall automation technology has increased productivity by 5–10 per cent through improved consistency[6].

Rather than relocating some crew members permanently from underground to the control room, the miners rotate between the surface and underground on different shifts. This is beneficial in rotating exposure to the physically sedentary but cognitively demanding control room work across miners as well as maintaining underground knowledge and skills. While decreasing safety and health risks, further automation will reduce these rotation opportunities.

Although the control room interfaces (Figure 12) provide extensive information sources, it was noted by operators that direct perceptual cues available in sound, equipment vibration, and vision of locations other than where cameras were placed were unavailable. Communication between surface control room and underground workers at the longwall was difficult at times and left room for improvement.

---

[6] https://www.csiro.au/en/work-with-us/industries/mining-resources/mining/longwall-automation

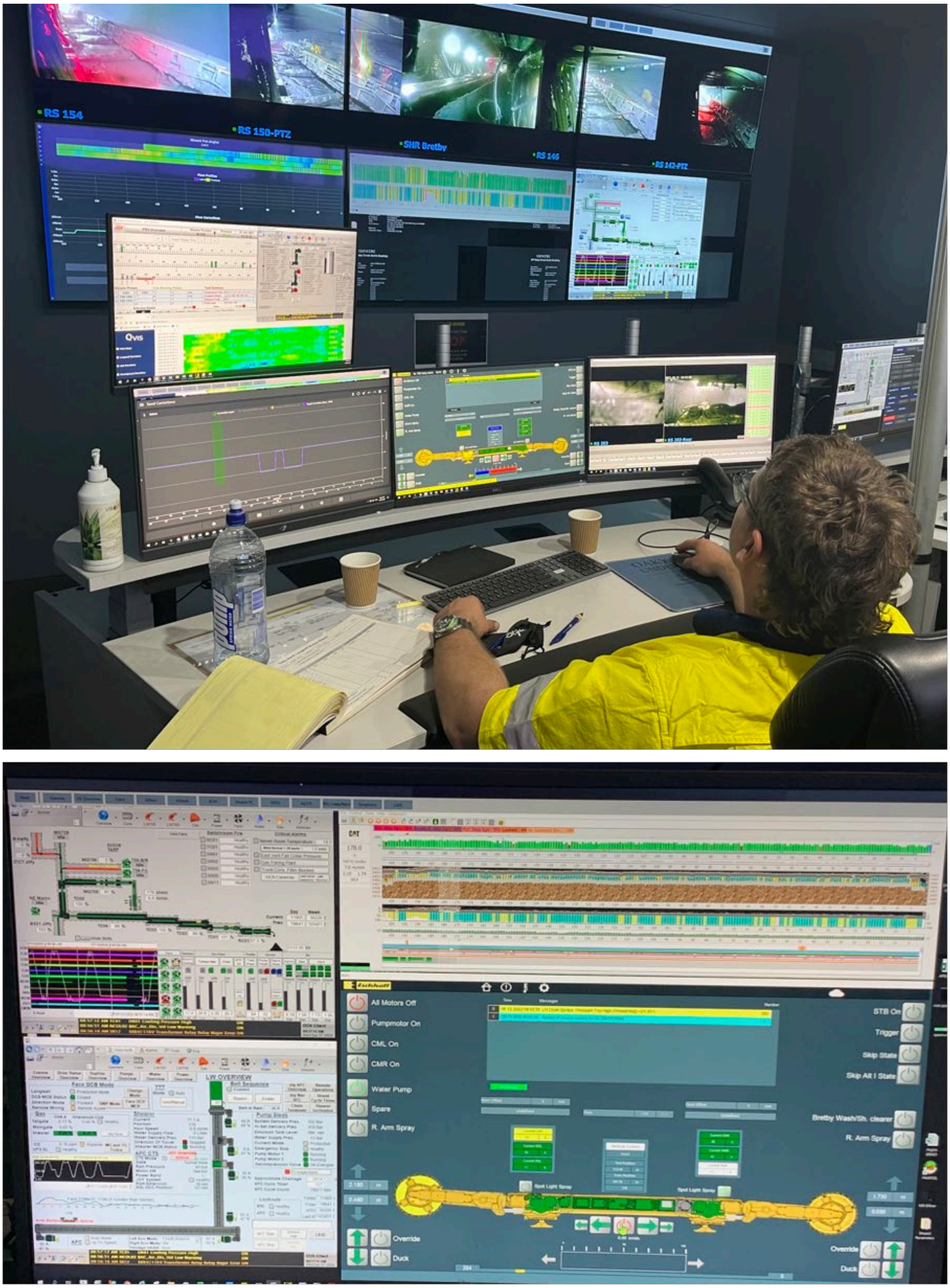


Figure 12: Automated longwall control room and interface screen at an Australian underground coal mine. (Image credit: Danellie Lynas).

Surface mining equipment

Haul trucks

Autonomous haul trucks have been in use at surface mines for more than 10 years. More than 1000 trucks are in operation globally and the number continues to increase rapidly. Safety has been an over-riding concern of both equipment manufacturers and mining companies. The systems currently in operation are safe, in that the overall collision risk profile appears to be lower than manual truck operations by an order of magnitude. However, there are aspects of the current implementations that deserve attention and improvement.

In addition to the automated haul truck related incidents described in the previous section, several other examples of incidents were identified.

- A software error allowed a controller to bypass an interlock and manually dump a truck at a crusher that was closed.
- Trucks' object detection systems are not effective in reverse and it was reported that collisions have occurred when there is an obstacle behind a truck that was not identified by the system.
- A procedural breach occurred that allowed a service vehicle not fitted with site awareness technology to travel through an autonomous zone without an escort.
- Potential for truck-pedestrian interaction during refuelling was noted if the mode changing process was not undertaken correctly.

Another issue of concern identified by key informants was software change management. Considerable effort is required on behalf of mines to test the functioning of updates before installing updates because of the potential for software errors to be introduced. The extent of the effort was considered to be, in part at least, because of limited information provided by equipment manufacturers about software changes.

The autonomous trucks and associated technology, and the people in both the control room and the field, form a joint cognitive system. Timely and appropriate decision making requires the joint cognitive system to maintain an accurate understanding of the state of the system and the environment to allow prediction of likely future events. No one person in the system has access to all the information required to maintain this situation awareness. Rather, the situation awareness is distributed across the system. Maintaining accurate distributed situation awareness is a dynamic and collaborative process requiring moment-to-moment interaction between team members and technology.

For example, the control room operator does not have direct access to information about roadway conditions and relies on people in the mine to provide the information required to allow appropriate decisions to be taken, such as slowing trucks to avoid loss-of-traction events. Similarly, the controller has access to system wide information that needs to be communicated to field roles. Communication between team members is clearly a critical aspect of maintaining accurate situation awareness, as is acquiring and interpreting information from autonomous system interfaces. Automated haulage control rooms are typically initially located at mine sites, however increasingly the controllers are being moved to remote operations centers (eg., Figure 13) which exacerbates this issue.

Some limitations in the design of the physical aspects of the controller workstations were noted such as high monitor positions leading to head and neck extension and increased visual demands, sometimes improved by the use of standing workstations (Figure 14). Input interface requirements also necessitated excessive pointing device use. Short-comings in control room interfaces were highlighted by informants (Figure 15). While it was indicated that mechanisms exist for providing feedback to the system designers, the consensus was that the response time for any changes is likely to be long.

An example of the importance of interface design is also evident in the role of site awareness systems provided within manually operated vehicles in the autonomous zone to assist operators to predict the future movements of autonomous trucks (Figure 16). Limitations in the effectiveness of these interfaces were noted in several of the collision near-miss incidents described in the Western Australian database.

A water cart operator reported that the introduction of autonomous haulage coincided with increased rough roads and suggesting that attention to wheeling offsets is required to avoid "tram tracks", especially at intersections. It was also suggested that the improved efficiency of autonomous haulage increases excavator operator workload because of the constant loading required.

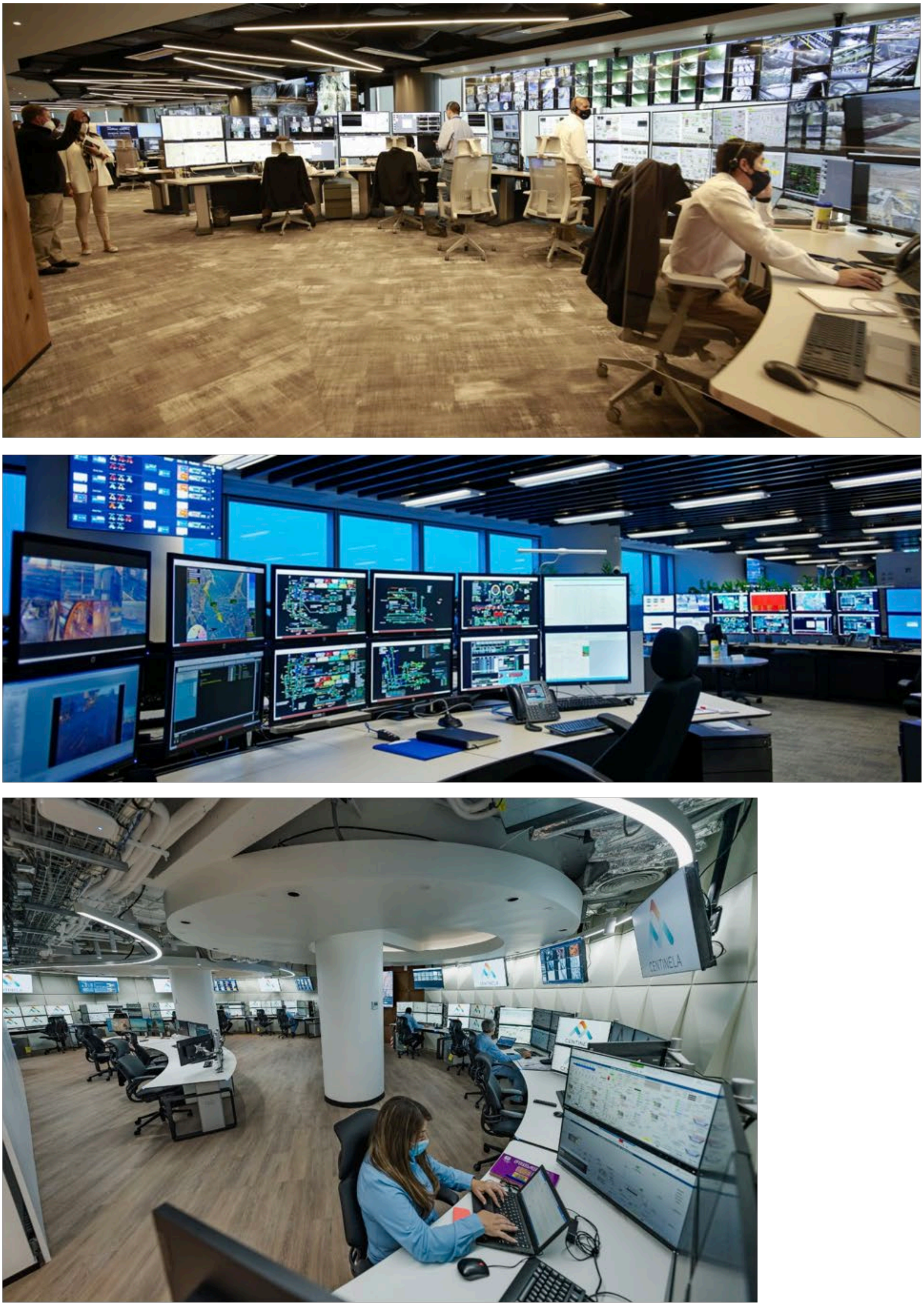


Figure 13: Integrated Remote Operating Centers. Top: Anglo American IROC Santiago (Moore, 2023b). Middle: BHP IROC Perth (Barndon, 2023). Bottom: Centinela IROC Antofagasta (Moore, 2022)

https://www.businesswire.com/news/home/20211110005520/en/

Figure 14: Automated haulage control workstations.

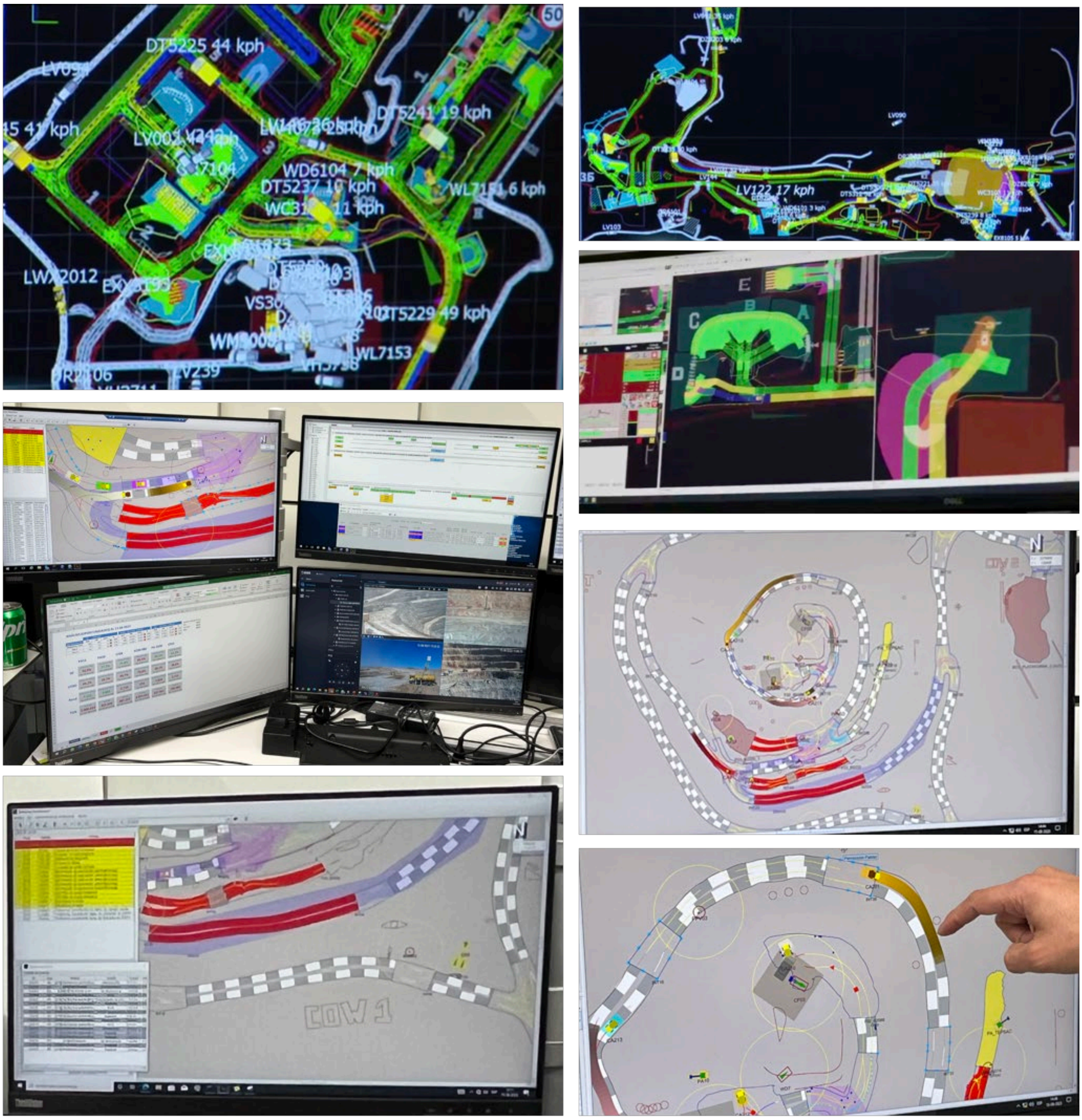


Figure 15: Autonomous haulage control room interfaces.

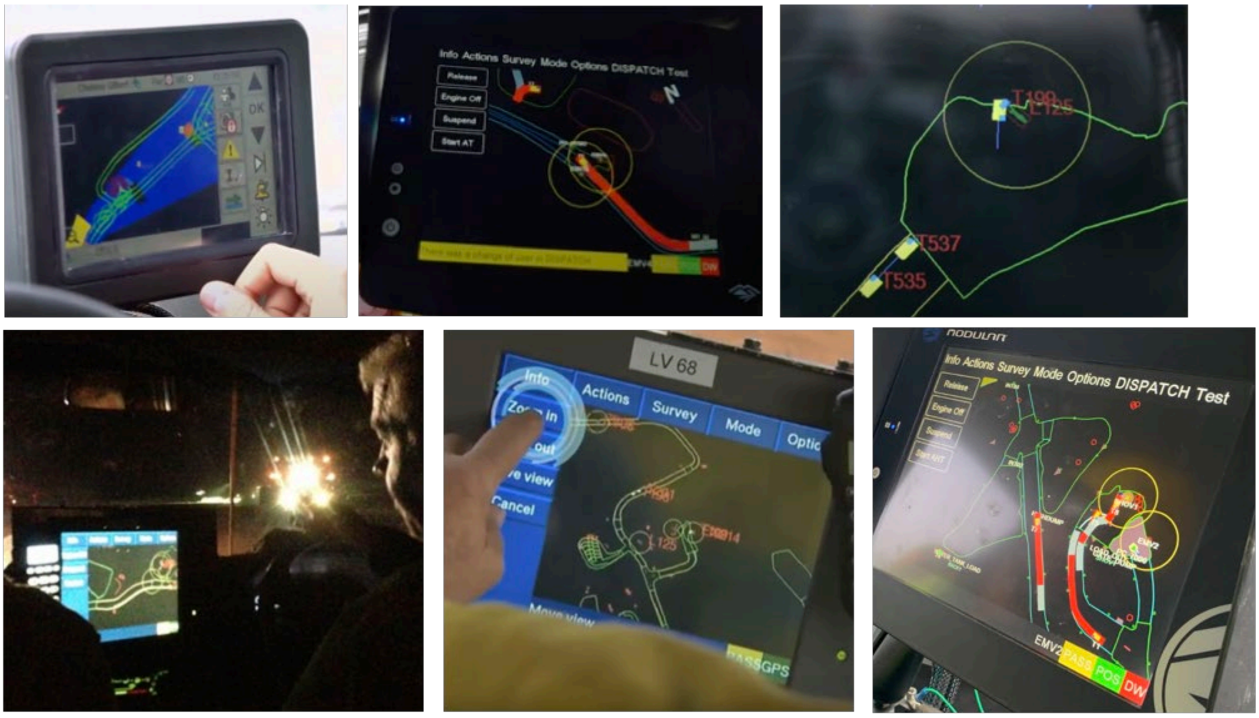
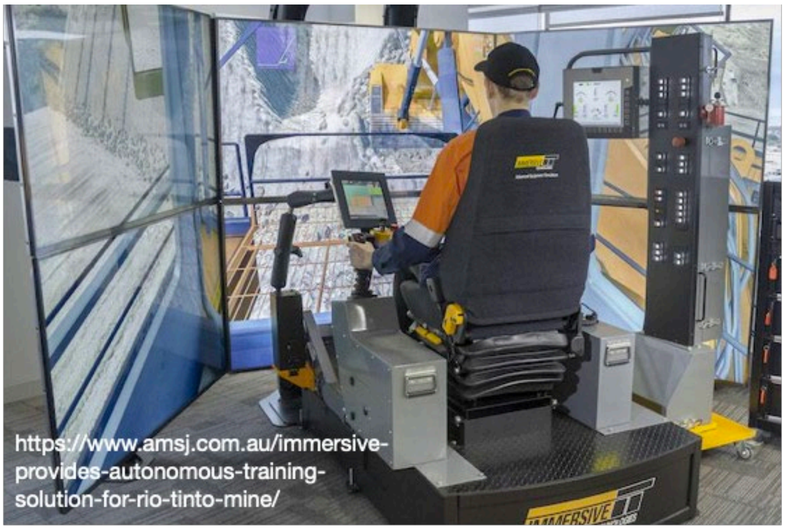


Figure 16: Site awareness interfaces provided within manual vehicles operated within autonomous zones at surface mine sites.

While most mines that have introduced autonomous haulage in the past have separated manually operated trucks from autonomous, more recent installations are mixed fleets. For example:

> "We are mixing the fleet as we need to introduce the autonomous trucks as fast as we can over time and also because we have quite a complex haulage circuit at the mine that would make it too difficult to be running two separate and distinct fleets. To get 100% autonomous we need 82 trucks to be converted so we still have a long way to go. Simply speaking, the way it is set up, the autonomous trucks recognise and treat the non-autonomous trucks as autonomous for the purposes of the system." (Moore, 2023b)

A recent green field coal mine in Australia has made the decision to utilize automated haulage fleet to haul overburden, while a manual fleet will be used to transport coal. The fleets will run to different diggers and dump points but share main haul roads. This site reported that the greatest challenge encountered had been the volume of training required to ensure all staff on site understood how to interact safety with the autonomous haulage. Training includes, for example, training for the excavator operators who will be loading autonomous trucks. Virtual simulation is typically utilized (Figure 17).



https://www.amsj.com.au/immersive-provides-autonomous-training-solution-for-rio-tinto-mine/

Figure 17: Virtual excavator simulator used for training operators to interact with autonomous haulage.

Selection and training were common themes discussed. For example, at a Chilean site the the transition to automated haulage began by interviewing over 200 of their employees for positions within the autonomous system. Each candidate was evaluated for their trust in autonomous systems, their willingness to retrain and their interested in the technology. Commitment and enthusiasm was considered more important than age and 80 of the employees were accepted and transferred. These operators began an extensive training program involving learning the operation of the autonomous system and particularly how to predict impending difficulty early enough to stop the sequence and take appropriate action. Extensive use of simulators was made and a system of certification levels based on simulator hours was introduced. A new maintenance-training program was established to ensure the trucks experienced maximum up time. Other skills needed were programming, communications skills (communication with the control system), and cyber security control measures.

Automated haulage control room roles involve high cognitive workload that may lead to performance decrements and/or adverse health effects. An experienced Australian trainer confirmed that "burn-out is a big thing" for controllers. As well as the potential impacts on operator well-being and sub-optimal performance, there are implications for turn-over, and subsequent recruitment and training costs.

Autonomous control room workload issues were noted by Pascoe (2020). For example, a controller interviewed explained that:

> "Previously for a manned operation you wouldn't, you have 40 trucks drivers that can think about it and do it yourself. You've got one controller, on average, looking after 25 trucks, with one builder. Planning all the work for those 25 trucks, as well. So, it's constant just churn; it doesn't stop; it's relentless…" (Pascoe, 2020; p. 157)

The workload is unpredictable, and this also increases stress. As Pascoe et al (2022c) noted:

> "Supervisors can be completing monitoring tasks and simultaneously be confronted with network outages, truck slides and broken-down machines" (p. 33).

Interruptions to work were also noted by operators as a source of stress, for example, routine site access requests interrupting building work that requires sustained concentration.

Chirgwin (2021a) similarly notes high autonomous controller workload across multiple control rooms:

> "Several controllers that had experience in manned and autonomous operations had assumed that automation would make their work life easier, but the experience was the opposite and their workload, cognitive load and communication responsibilities had increased because of automation" (p. 7)

and observed that the workload is also increased by allocation of additional, perhaps unnecessary, tasks:

> "… many organisations continued to hold on to outdated ways of working, and … continued to add tasks to the controller role. An example of this is the insistence of manual reporting. Despite the fleet systems having the ability to capture multitudes of data, all of the controllers interviewed reported that they were required to manually report on what was occurring during their shift and justifications for their actions. This task was largely seen as a task given to the controller with the aim of saving someone else time …" (Chirgwin, 2021a, p. 7).

Controller workload is also increased by the extent of communication required with people in field roles. The requirement for the control room to monitor and respond to multiple communication channels (radio, telephone, in-person) creates potential for frustration, interpersonal conflict, and cognitive overload. The multiple communication channels means that the field staff do not know if the control room operator is already attending to another information source. They may also not appreciate the time required to action a request before the next request can be attended to. For example, an operator was observed exhibiting frustration when a second two-way radio call was received while he was still navigating the complex software interface to action a request received a moment before, saying, "don't they listen to each other". This also led to extra workload for the control room operator to ask the second field operator to repeat their request. Interpersonal group dynamics appeared to be important in this situation, particularly rapport between control room operators and field staff where interactions are largely virtual, and particularly if the controller has limited previous field experience.

The rapid expansion of autonomous haulage has resulted in mining companies encountering considerable difficulties attracting, training and retaining controllers. This has become a vicious cycle, in that the scarcity of controllers results in high workloads, leading to burn out, exacerbating the issue. Chirgwin (2021a) paints the picture she observed in multiple control rooms:

> "…controllers were often observed being on-shift before mining production employees, and were often the last to leave, going beyond their allocated 12hr shift. It was not uncommon to see a controller not take a break (including a toilet break) for up to 6h, and sometimes that extended to the entire shift. … Often there was no-one to replace the controller for their break, so they would either not have one, or the other controllers or their supervisor would take on the additional workload for that break period."

The shortage of controllers leads to difficulty releasing staff for training that, in turn, also contributes to increased stress and reduced job satisfaction.

Blast-hole drills

Removing the operator from blast-hole drill rigs removes exposure to dust and vibration, access and egress risks, and safety risks associated with vehicle travel within the mine. The advantages for one operation were described:

> "From our point of view in operations, what we are looking for is the precision of the process, which in drilling still depends a lot on the human factor. But before this depended on an operator in the cabin who is exposed to risk – they are often close to the highwall, or close to bench edges or ore faces. So to remove the operator from the cabin and put them in the IROC actually improves the utilisation of the fleet while also improving the quality of life of the operator – no exposure to noise, vibration or climate extremes like cold. But it is also more efficient – for example at site the operator has a one hour lunch break, but in addition to that time they come out of the cabin, travel for maybe 30 minutes to the canteen and then the same back again. So there is unavoidable underutilisation of the drill asset. Here, the autonomous drill operator still has a lunch break but eliminates all that site related extra time plus the climate extremes and high altitude of being at the site. Plus the machine continues to drill anyway during lunch breaks and shift changes." (Moore, 2023b)

Another operation reported a 37% increase in drilling rate and improved accuracy; as well as increased availability (Ellis, 2023).

Several different approaches to autonomous drill rig workstations have been taken. In some cases, the physical controls of the drill rig have been replicated in a control room. For example, the workstation illustrated in Figure 18 is used to control three automated drill rigs.

Figure 18: Replica drill cab workstation and interface for automated drill rig. (Westrac, 2022).

Other approaches are illustrated in Figure 19, where joysticks are provided but abstracted from a drill cab context.


https://www.bnamericas.com/en/news/chile-has-another-automated-mine

Eastwood, 2023

Figure 19: Joystick controls for automated drill rigs. Top: Anglo American IROC, Santiago, Chile. Bottom: Lake Vermont mine, Australia. (Eastwood, 2023)

Another approach is illustrated in Figure 20. Multiple video camera feeds provided a 360 degree view from the drill rig, and from a remote viewpoint, assisting the remote operator to maintain global and local situation awareness.

The visual interfaces previously provided within the drill cab are replicated; however the controls located within the manual cab have been replaced by a wireless Xbox controller. The controls on the wireless Xbox controller cause different actions in each of three modes of operation (drill mode, setup mode and propel mode). This creates the potential for mode errors. The probability of mode errors may be reduced by ensuring that the current mode of the machine is readily apparent to remote operators. Auditory feedback may provide a means of identifying machine mode that does not rely on visual attention.

Operating a control in a direction, which causes an effect opposite in direction to that intended, is another potential error mechanism. The probability is reduced by ensuring directional control-response compatibility (Burgess-Limerick et al., 2010). Determining the appropriate directional control-response relationship is complicated in this situation because the orientation of the wireless remote control may vary during use, however there does seem to be a potential inconsistency in the directions chosen for "hoist", "jack up" in drill mode, "swing deck up" in set up mode (all upwards when the remote is in the orientation illustrated in Figure 21); and the control directions illustrated for "mast up" in the setup mode (the reverse).

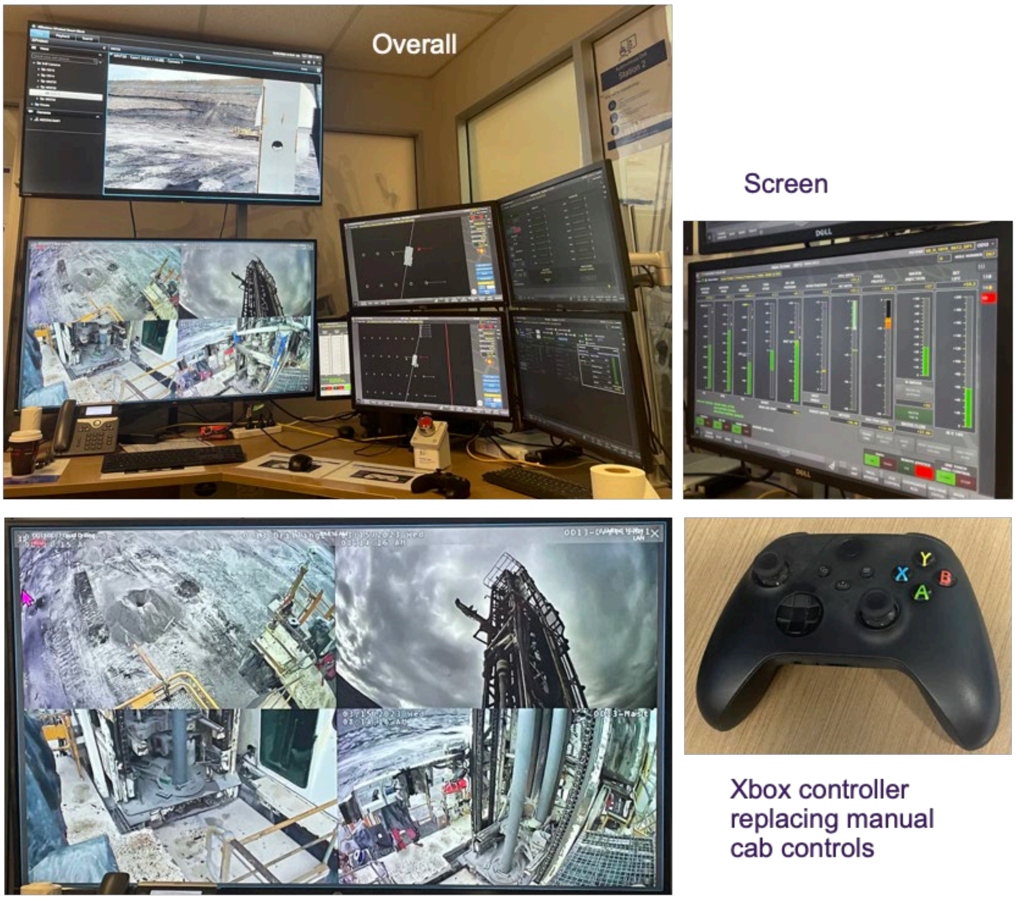


Figure 20: Autonomous blast-hole drill workstation and interfaces

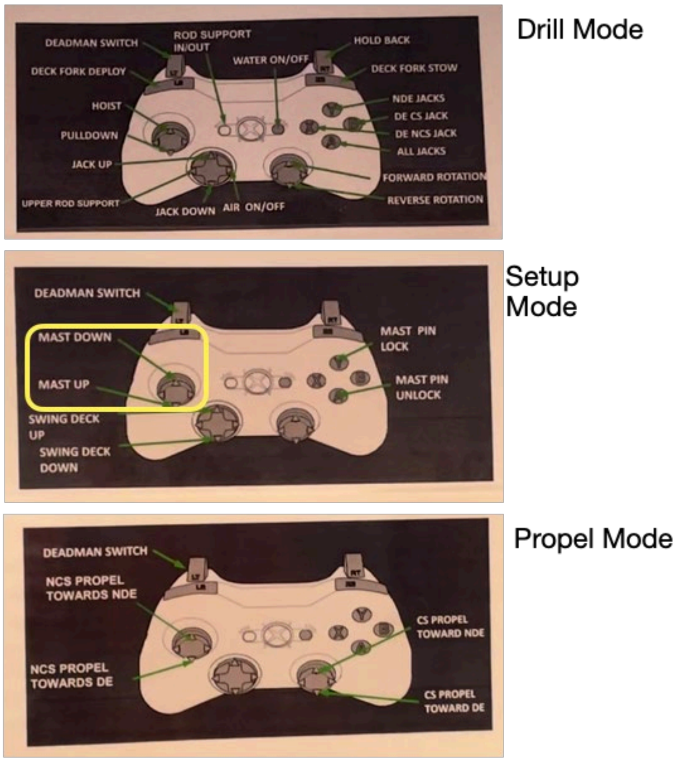


Figure 21: Remote-control drill functions in different modes

Dozers

Dozer automation was preceded by non-line-of-site remote control operation that was undertaken to remove human operators from hazardous areas such as stockpiles. The provision of interfaces to maintain situation awareness is relevant to both remote control and automation. Schiffbauer et al (2007) described a remote vision system intended for stock-pile dozer use (Figure 22), while an extended evaluation of different combinations of visual, auditory and motion cues for dozer teleoperation was undertaken as part of ACARP project C20021 (Dudley, 2014). Figure 23 illustrates the interface provided for these trials that incorporates machine instrument information and schematic information. The intended use-case was bulk dozer push at surface coal mines. Performance time for the remote dozer operation was increased over manual operation during a standardised dozer push task. Visual quality was found to be the dominant factor influencing performance. The provision of motion cues provided no additional performance benefit.

Figure 22: Video display arrangements suggested for remote stockpile dozer use by Schiffbauer et al (2007).

Figure 23: Interfaces provided for remote dozer interface experiments undertaken by Dudley (2014)

Interfaces currently provided for remote control dozers are illustrated in Figure 24. Again, instruments, including an inclinometer and an additional display to facilitate maintenance of situation awareness, supplement the video displays.

Figure 24: Dozer remote control interfaces.

The current iteration of the semi-automated dozer system described earlier (Figure 7 & 8) was observed being remotely supervised from the World Mining Congress exhibition hall in Brisbane while the dozers were in operation at a central Queensland coal mine, 600 miles away (Figure 25). Here the interfaces provided include both plan and elevation views of dozer position in addition to video feeds to aid the operator maintain situation awareness. In this case, one operator remotely supervises up to four dozers. Safety and health benefits include eliminating exposure to whole body vibration and other musculoskeletal risk factors, access and egress, and site transport risks.

The transition required extensive operator training, starting with two dozers and gradually working up to four. Utilisation has been increased 25% and productivity is enhanced by software that automates decision-making. Alterations to the production schedule were required to take advantage of the increased equipment availability (Gleeson, 2021).

Bulldozers are used on stockpiles to push material outward from piles created by stackers and subsequently retrieve this material by pushing it to reclaim valves. Remote dozer operation is undertaken in several international locations for similar reasons, for example. This is high-risk work because there is a risk of engulfment. The feasibility of utilising automated dozers for coal stockpile operations is currently under investigation (ACARP project C35036).

https://www.mining.com/web/caterpillar-collaborates-with-arch-coal-to-prove-semi-autonomous-dozers/

Figure 25: Semi-autonomous dozer workstations, 2015 (left) & 2023 (right).

Relevant guidelines & standards

Mining automation standards and guidelines

Albus, J. Quintero, R., Huang, H-M & Roche, M. (1989). Mining automation real-time control system architecture standard reference model (MASREM). NIST Technical Note 1261 Volume 1.

Sponsored by the US Bureau of Mines, the "Mining automation real-time control system architecture standard reference model" was "intended as a reference document for the specification of control systems for mining automation projects….provides the high-level design concepts to be used in the automation of a mine." Given the cover image is a stylised underground coal continuous mining machine, it can perhaps be assumed that underground coal mines were the initial target. The advice provided remains relevant.

The document includes sections discussing the role of humans in the system, viz.,

> "The sharing of command input between human and autonomous control need not be all or none. The combination of automatic and operator modes can span an entire spectrum from one extreme, where the operator takes complete control of the system from a given level down so that the levels above the operator are disabled, to the autonomous mode where the operator loads a given program and puts the mining machine on automatic. In between these two extremes is a broad range of interactive modes where the operator supplies some control variables and the autonomous system provides others. … Even in cases where the operator takes complete control, some of the higher level safety and fault protection functions should remain in operation." p. 19-20.
>
> "The operator interfaces allow the human the option of simply monitoring any level. Windows into the global memory knowledge base permit viewing of maps of a section, geometric descriptions and mechanical and electrical configurations of mining machines, lists of recognized objects and events, object parameters, and state variables such as positions, velocities, forces, confidence levels, tolerances, traces of past history, plans for future actions, and current priorities and utility function values. These may be displayed in graphical form; for example, using dials or bar graphs for scalar variables, shaded graphics for object geometry, and a variety of map displays for spatial occupancy. Time traces can be represented as time line graphs, or as stick figures with multiple exposure and time decay. …
>
> Geography and spatial occupancy can be displayed as a variety of maps, vectors, or stick figures, or shaded graphics images. … The operator may also have a direct television image of the mining machine's environment with graphics overlays which display the degree of correlation between what the mining machine believes is the state of the world and what the human operator can observe with his/her own eyes." p. 21
>
> "The human operator can thus monitor, assist, and if desired, interrupt autonomous operation at any time … to take control, to stop the mining machine, to slow it down, to back it up, or to substitute the human's judgment by directly entering commands or other information to replace what the robot had otherwise planned to do." p. 22

A (brief) "Safety System" section was also included, reproduced here in its entirety.

> "The mining machine control system should incorporate a safety system which can prevent the mining machine system from entering forbidden volumes, both in physical space and in state space. This safety system should always be operational so as to prevent damage to the mining machine or surrounding structures or humans during all modes of operation: teleoperation, autonomous, and shared.
>
> The safety system should have access to all the information contained in the world model of the control system, but should also maintain its own world model, updating it with redundant sensors. The safety system should periodically query the control system to test its state and responsiveness. Conversely, the control system should also periodically query the safety system to test it. Observed states should be constantly compared with predicted states and differences noted. If either system detects an anomaly in the other, error messages should be sent and appropriate action taken." p. 22.

Department of Mines and Petroleum (2015). Safe mobile autonomous mining in Western Australia — Code of Practice.

The code of practice provides guidance for mobile autonomous and semi-autonomous systems used in surface and underground mines in the Australian state of Western Australia. The document adopts a conventional risk management approach and notes that autonomous mining may bring additional risks. A general duty of care that applies to all stakeholders is noted, and the code encourages "continuing communication and consultation between system and component suppliers and the mining operation" (p. 2).

The code defines responsibilities for two groups: system builders — those who supply the automation; and system operators — those who use the automated mobile equipment.

Amongst other responsibilities that include determining functional safety requirements and establishing performance requirements, system builders are required to share residual risk information with the system operator. Responsibilities of the system operators include: understanding the risks including any residual risks, developing safe work procedures, consultation with workers, providing training, and investigating incidents.

Three questions are posed for the risk management process:

- "What are the potential scenarios for mobile autonomous mining incidents?
- What are their potential consequences in terms of safety and health?
- What controls are available and how effective are they?" (p. 4).

Starting with these questions is more effective than commencing with considering failure modes because it encompasses the possibility that incidents with potential adverse consequences may arise in the absence of the failure of any system component. Appendix 6 of the code of practice provides examples of incident scenarios, including:

- unauthorised access of personnel or equipment into autonomous area
- autonomous equipment going into unauthorised areas or performing tasks that cause safety risks (it is suggested that this may occur due to human errors such as overriding an alarm condition, or failure to update a map)
- communications failure
- autonomous equipment loss of traction
- failure to communicate system changes
- unintended traffic interactions
- inadvertent switching between modes
- interactions with pedestrians
- remote re-starting of autonomous vehicle from an inappropriate location
- fire

Risk identification techniques nominated include HAZOP and LOPA, and reference is made to functional safety analysis. The code of practice recommends that:

> "those undertaking a risk assessment have the necessary information, training, knowledge and experience of the:
>
> - operational environment (e.g. scale, complexity and physical environment of mining activities)
> - operational processes (e.g. maintenance systems, work practices, interaction, separation)
> - autonomous systems (e.g. functionality, safety features)." (p. 4).

While these areas of expertise are no doubt important, the code of practice is deficient in failing to identify the understanding, training, knowledge, and experience of humans as critical to the risk assessment.

Emphasis is placed on the importance of higher order control measures, monitoring and review, and documentation of the outcomes of the risks assessment process and subsequent monitoring activities in the operation's risk register.

The importance of training is highlighted in the code of practice. It is noted that personnel must be provided with the knowledge and skills required to perform required tasks and particularly how to recognise when the system is not operating as intended, and what actions to take in such situations. A requirement for evidence-based assessment of competency is highlighted, as is the importance of consultation, retraining, and reassessment whenever changes are made to the systems of work. Supervisors are identified as a "fundamental safety function", with responsibilities including ensuring work is carried out as intended and verifying that the system continues to function safely.

Section 5 of the code of practice focusses on mine planning and design for controlling hazards. It is suggested that mine design should be suitable to autonomy and aim to minimise interaction with people and manual equipment. Attention is directed, in particular, to road design, traffic management (including intersections, load and dump locations, access controls) and separation of autonomous equipment from people and manual equipment.

Section 6 of the code of practice places particular emphasis on the role of "functional safety" standards, suggesting that:

> "Functional safety provides assurance that the safety-related elements of the autonomous system and operational controls provide suitable risk reduction to achieve the safe operation of the autonomous systems." p. 12

While functional safety approaches are important for assessing the reliability of individual components in the system, the faith that this assures safe operation of the entire system is misplaced. The code of practice does note at this point the relevance of human interactions with the autonomous systems and the potential impact of human behaviors for the assessment of risks.

Section 7 of the code of practice lists issues to be addressed during commissioning including "functional and user acceptance testing"; however the code is silent on the involvement of the real users, that is the people who will be required to work with the system, during this acceptance testing.

Section 8 of the code of practice highlights "operational hazard controls", listing issues to be addressed by operational practices. The importance of supervision, training, and competency assessment, and change management is reiterated. Equally important is directing attention to (1) rules governing changes between autonomous and manual operating modes, and (2) travel management rules that govern interactions between autonomous equipment, manual equipment, and pedestrians. At this point "human factors (eg., response to system information or warning, adherence to exclusion zones)" (p. 13) is listed a matter to be addressed within operation practices, along with area security and control. This is too little, and too late!

Section 9 of the code of practice notes that maintenance hazards also require consideration. Attention is directed to a series of issues including functional safety considerations for system maintenance, recovery procedures in autonomous areas, and area and activity isolation. The final section of the code provides recommendations related to emergency management.

ISO (2019). Earth-moving machinery and mining — Autonomous and semi-autonomous machine system safety. ISO 17757: 2019

The ISO standard for autonomous and semi-autonomous machine (ASAM) system safety specifies safety criteria and guidance on safe use. The standard also provides definitions for terms related to such machines.

ISO 17757 stipulates that a risk assessment process shall be completed for autonomous and semi-autonomous machine systems according to the principles described in ISO 12100: 2010 Safety of machinery — General principles for design — Risk assessment and risk reduction (ISO, 2010). This standard, in turn, provides a strategy for risk assessment that stipulates that the designer shall: (1) determine the intended use and foreseeable misuse of the equipment, (2) systematically identify the hazards and associated hazardous situations, (3) estimate the risk for each circumstance and hazard, (4) evaluate the risk, and (5) eliminate the hazard or reduce the risk.

Task-based risk assessment is required in that the hazardous situations referred to in Step (2) of this strategy are defined as circumstances in which a person is exposed to a hazard. The standard requires the systematic identification of these circumstances, and notes that to achieve this it is necessary to:

> "identify the operations to be performed by the machinery and the tasks to be performed by persons who interact with it, taking into account the different parts, mechanisms or functions of the machine, the materials to be process, if any, and the environment in which the machine can be used. ... All reasonably foreseeable hazards, hazardous situations or hazardous events associated with the various tasks shall then be identified". (ISO 12100 Section 5.4, p. 15)

Further, ISO 12100 Section 5.2 stipulates that the information required for risk assessment (analysis and evaluation) should include the experience of users of similar machines and, wherever practicable, an exchange of information with the potential user. That is, ISO 12100 requires task-based risk assessments, and recommends user involvement. ISO/TR 14121-2 Safety of machinery — Risk assessment — Part 2: Practical guidance and examples of methods (ISO, 2012) similarly notes that the team conducting a risk assessment should include those with actual experience of how the machine is operated and maintained. This is now possible for many autonomous and semi-autonomous machines given the growing number of global implementations.

Appendix A of ISO 17757 provides a consolidated list of the failure modes identified in the standard specific to autonomous and semi-autonomous machines. The focus on failure modes neglects the potential for unwanted outcomes to occur in complex systems even though all systems function as intended. Appendix B provides further guidance for managing risks specific to autonomous and semi-autonomous machines. The Appendix draws on the content of the Western Australian code of practice, and shares its failure to identify the importance of an understanding of human factors to the risk assessment.

Section 4 of ISO 17757 requires compliance with functional safety performance levels for the *safety-related parts* of control systems. The standard goes on to specify requirements for specific features including remote stop systems, visual indication of operating mode, and it modifies existing standards for braking systems and steering to be suitable for autonomous and semi-autonomous machine systems.

The standard identifies errors in the positional and orientation systems utilized by autonomous and semi-autonomous machine systems as creating risks of unwanted outcomes including collisions with other vehicles. A range of potential failure modes are identified and such systems are required to have the means of detecting the accuracy of the position and orientation data. The systems are required to maintain a safe state when the data is not of the required precision and accuracy (presumably as determined by the risk assessment). Sufficient sensor redundancy is required by the standard to allow a safe state to be maintained in the event of failure of one means of determining position.

Where a digital terrain map (i.e., a topographical description of the site in digital format) is used to maintain safe operating conditions, ISO 17757 requires that the system shall monitor the validity of the map and maintain a safe state in the event of insufficient accuracy of the map (again reliant on the risk assessment to define sufficiency). The standard highlights mechanisms by which the map used by the autonomous system may become inaccurate, including roadway deterioration or changes, calibration or alignment error, or an incorrect version of the map being loaded on the autonomous machine. It is also noted that sudden terrain changes may not be able to be responded to — highlighting a residual risk of failure.

Perception systems (as defined by ISO 17757) are sensors that capture information about the autonomous machine's surroundings. This information is subsequently analysed to detect and classify features or objects of interest. The purpose of such perception systems is to provide information for the safe autonomous control of the machine. A range of failure modes for such object detection systems are identified, including: occlusion by contaminants on the sensor; poor lighting; uneven ground; machine vibration causing sensor misalignment; objects too small, or moving too fast to be detected; transparent or dark objects; or a delay in classification caused by other applications overloading the processor used for detection or classification. The possibility of false detections is also highlighted, as is the possibility of inaccuracy in the location of detected objects, or misclassification. The accuracy of the classifier is in part dependent on the quality of the training of the classifier.

Having defined these potential errors, ISO 17757 then stipulates that: the requirements of the perception system shall be based on the risk assessment; the perception system shall maintain the safe state of the autonomous machine during any interaction with its intended operating environment; the autonomous machine system shall detect when the perception system is not meeting the minimum requirements (as determined by the risk assessment) and both maintain the machine in a safe state and inform the (human) supervisor.

Errors in navigation of the autonomous machine are identified as resulting in risks of collisions with other equipment, infrastructure, or people. Such errors are identified as potentially resulting from inaccurate position and orientation information, incompatible coordinate systems, imprecise navigation control, poor planning or an inaccurate digital terrain map. The standard requires the autonomous machine system to maintain a safe heading and velocity when operated in accordance with the specified operating environment and conditions; to identify if this is not the case and if so, to take action to maintain a safe state; and to identify the human supervisor. A potential role for a "competent person" in validating paths or areas to be used by the autonomous machine is also noted.

The role of task planning is noted to vary greatly depending on the machine and the application. Risk identified with task planning are that the autonomous machine could be directed to travel a non-trafficable path or a hazardous path, or to undertake an activity that has undesirable consequences for another machine or person. The standard requires that all such risks: "Shall be noted and mitigated as part of the risk assessment process" (p. 16).

A potential role for humans in assisting the task planner to avoid errors is also noted:

> "The task planner shall avoid directing the ASAM onto a known hazardous path. The hazard level of the path may be determined either by the ASAMS or humans interacting with the ASAMS or some clearly defined combination of the two. If the ASAMS is responsible for determining the hazards associated with a path, then the ASAMS shall be able to determine all reasonably anticipatable hazards and have a means to inform the task planner of the detected hazards." (p. 16)

Section 10 of ISO 17757 highlights the importance of communications and networks to the safe operation of autonomous and semi-autonomous machines in mining. Communication failures are associated with a range of risks including: loss of remote stop ability; loss of access to situation awareness information; lost or delayed command input; or inaccurate position information. The autonomous machine system is required by ISO 17757 to maintain safe operation in the event of any communications-related failure.

Section 11 of ISO 17757 concerns the supervisor system, including sub-systems such as: user interfaces, mission planner, remote control, and configuration management. Risks identified with these systems include incorrect assignment or command provided to the autonomous machine, operation with an incorrect map, or use of incorrect machine parameters. Little guidance is provided regarding the control of these risks.

Section 12 concerns access to the autonomous zone, permissions and security. Parameters are provided to be taken into account in the risk assessment through which the access control details will be determined. Risks identified in section 12.3 Operational Risks include several related to human interaction with the system including: "access to the autonomous zone by unauthorised people or equipment"; "ergonomics or human factors that can lead to unexpected switching of operational mode with loss of control"; "improper capture of changes to work areas, especially before switching work areas between manual and autonomous"; "incomplete or improper system updates and changes to programming"; "improper road design, area demarcation or other human errors". Section 12.4 highlights risks associated with mode changes and requires a means to prevent changes that lead to an unsafe condition, including the prevention of unintentional mode change caused by a single human error; and the ability to engage the autonomous mode from a safe position.

ISO 117757 places responsibility for the provision of documentation including manuals, specifications, operating instructions and training documentation on the system integrator. Section 13.4.2 outlines broad training requirements, including: system functionality and hazards and risks, what to expect if environmental or operational conditions change, and how to recognise when machines are not operating as intended, and what actions to take in response. Echoing the Western Australian code of practice, ISO11757 requires evidence-based assessment of competency and suggests that affected personnel should be consulted, retrained as necessary, and reassessed whenever work procedures or plant and equipment change.

GMG (2019). Guideline for the implementation of autonomous systems in mining.

The Global Mining Guidelines Group (GMG) is a not-for-profit organization founded in Canada in 2012. Corporate members include mining companies, equipment manufacturers, and service providers. The GMG guideline aims to provide information to facilitate the implementation of autonomous systems. It includes reference to safety aspects, as well as information on developing a business case, regulations, social impacts, and deployment issues. The safety material is envisaged to form part of an implementation plan describing a risk management process following ISO 17757.

The knowledge identified as necessary for the risk assessment is expanded beyond that identified in the Western Australian code of practice and ISO 17757 to include the "Site continuity plan" and "Corporate risk guideline". Again, the opportunity to note the importance of an understanding of human behavior was missed.

The role of humans is acknowledged briefly at the conclusion to this section, viz.:

> "When determining how to implement various controls, mine sites must ensure they provide sufficient information for decision-making. Though the systems are autonomous, human decisions are still required to overcome exception states for autonomous systems at all maturity levels. The system should be designed such that alerts and alarms on the machines and in the control room are prioritized with humans in mind." (p. 13).

This text makes it clear that the role of humans is considered to be of peripheral importance, envisaged as exception management only. This view is reinforced through a figure provided to illustrate the "key considerations for a design management framework for mining automation". Human-Systems Integration, while acknowledged, is relegated to the periphery as a "broader design context" along with "environmental and social considerations".

However in Systems Engineering (as defined by the International Council on Systems Engineering, 2015), Human-Systems Integration refers to engineering processes that ensure that human-related issues are adequately considered during system planning, design, development, and evaluation — of which safety and health issues are a subset, along with training, human factors engineering, and staffing decisions.

NSW Resources Regulator (2020). Autonomous mobile mining plant guideline. DOC20/690069

The New South Wales Resources Regulator is a state government agency that is responsible for regulating health and safety for the mining and petroleum industry in the Australian state of New South Wales. The autonomous mobile mining plant guideline summarises the regulator's requirements for sites intending to implement autonomous equipment. The guidance acknowledges the potential safety benefits of automation while noting the potential for new risks to be created. Examples of such new risks are suggested to include:

> "automation associated with longwall mining equipment has created new risks, such as being crushed by an automatically advancing roof support" (p. 4).

The potential for loss of direct perceptual information is noted.

The guideline describes the legislative requirements applicable in New South Wales. In addition to a duty of care imposed by the Work Health and Safety Act, mining specific regulations impose duties that include conducting risk assessments:

> "with appropriate regard to the nature of the hazard, the likelihood of the hazard affecting the health and safety of a person, and the severity of the potential health and safety consequences" (p. 4).

The guideline directs mine operators to pay particular attention to interactions between people and autonomous machines, noting:

> "While autonomous operation, by definition, means there will not be people onboard machines, it does not mean there will be no people in the autonomous operating zone (AOZ). There are tasks such as workplace inspections, machinery inspections, maintenance tasks and repairs. The intent of these tasks is to ensure a safe work environment and the correct operation of the autonomous machines and other plant. Other activities form an essential part of the mining process, such as road maintenance, operator change-over for manually controlled plant and operating service and ancillary vehicles.
>
> Risk assessments for the introduction and operation of autonomous machines must consider all foreseeable scenarios where it is possible for people to interact with the machines, or where the machines may interact with other equipment or infrastructure." (p. 8).

The NSW regulator adopts the approach described by the ICMM Health and safety critical control management implementation guide (ICMM, 2015). Mine operators are directed by the regulator to identify critical controls to prevent incidents associated with autonomous machines, and to implement effective mitigating controls to protect workers in the event that an incident does occur. Consideration is directed to the full life cycle of the equipment.

It is suggested that a mine's critical control management process should include routine verification of the effectiveness of critical controls. Finally, the importance of change management is identified:

> "Mine operators must be vigilant in applying their risk management processes to changes as the operation of autonomous machines evolves and expands. The temptation to expand the scope and broaden the use of autonomous machines without appropriate risk management will lead to weakening or loss of existing controls. It may also lead to a failure to identify that additional controls are required due to the changes. Change management processes must be applied to all aspects of machine operation, including hardware and software, and should be used during the complete lifecycle of the machine, including commissioning, maintenance and repair activities." (p. 9).

Alberta Mine Safety Association (2020). Autonomous Haul Systems.

The Alberta Mine Safety Association is an industry association formed in 1982, comprised of representatives of mining, quarrying and oil sands operations in the Canadian province of Alberta. The guide is intended to provide "direction for the healthy and safe application and operation of autonomous technology in mining" for the province and purports to be "Accepted and Approved by Alberta Occupational Health and Safety". While the title of the document suggests a narrow scope, the guidance is intended to be applicable to surface and underground loaders, drills, water carts and other mobile auxiliary equipment.

The guide directs attention to the risk management framework provided by ISO 12100 and ISO 17757. Constant engagement with "frontline" personnel during the process is identified as "imperative". The importance of training and competency for anyone working in the autonomous zone is emphasised, and the contribution of humans to safe operation is identified viz.,

> "Although the operation is autonomous, there is a human element that must be accounted for so the operation can run safely. This risk can be managed through an organization willingness to:
>
> - give workers the training and time to build the necessary skill sets to operate within the AOZ safely
> - commit to regular discussions about automation project challenges and collaborate management strategies with front line workers.
> - apply best practice and sharing of information from previous autonomous operations for learning and to support new challenges within the autonomous project" (p. 7).

Additional guidance, including examples of hazards that may be encountered at pre-implementation, implementation, and operation stages, is provided.

Alberta Occupational Safety and Health (2020). Applying for Occupational Health and Safety autonomous haulage system approval.

The document summarises the steps required for a site to obtain approval to operate an autonomous haulage system. Documentation to be included in the application includes braking, steering and other primary system test results; as well as a detailed project management plan that is to "establish a thorough knowledge of the Autonomous Haulage System as well as the hazards and controls that are associated with the technology". A detailed outline of the topics to be addressed in the plan is provided, and this includes a safety management plan. A range of additional appendices are required — including a letter from the manufacturer indicating compliance with ISO 17757.

Mandela Mining Precinct (2021). Guideline: Best practice applications of mechanised equipment.

The Mandela Mining Precinct is a Public-Private Partnership between the South African Department of Science and Innovation through the Council for Scientific and Industrial Research, and the Minerals Council South Africa. The focus of the guide is on underground narrow reef hard rock mining in South African gold and platinum mines. The document draws heavily on the GMG (2019) guideline. Some country-specific issues are noted. For example, a tele-remote initiative at one site was abandoned due to union opposition.

The guideline suggests that: "All mine design and planning must incorporate safety by design" (p. 26) noting that design considerations include human/system interfaces; however, human aspects are notably absent from the list of topics to be considered in "safety by design". Attention is directed instead to a list of engineering standards provided by GMG (2019). Chapter 3 of the guideline provides general occupational health and safety considerations for mechanised mining systems. The importance of participation of all stakeholders in development of an occupational health and safety management plan is emphasised. Specific to automation, the following are suggested for consideration:

- "A real-time tracking system to flag personnel entering "no go" zones.
- A system to indicate personnel as either "at shaft" or "safe from shaft" when tagging in or out at the lamp room.
- Machines should have pedestrian detection systems to avoid injuries.
- With the potential reduction in ventilation requirements in autonomous operations, the real-time tracking system should be utilised as input to "ventilation-on-demand" systems." (p. 51)

Additional chapters of the guideline address regulatory requirements and change management.

Resources Safety & Health Queensland (2022). Autonomous mobile machinery and vehicle introduction and their use in coal mining. Queensland Guidance Note.

The guidance note was issued by the Mines Inspectorate to guide surface and underground coal mining operations in the Australian state of Queensland, drawing largely on the Western Australian code of practice. Responsibilities for the safe implementation of autonomous and semi-autonomous mobile machinery are broadly divided between system builders and system operators. It is suggested that the responsibilities should be defined and agreed by all parties.

It is noted that Input from many people is required for effective risk management. Those nominated are: "researchers, design engineers, project managers, team leaders, controllers, safety and health representatives, coal mine workers involved in the tasks, and emergency response personnel." (p. 8).

The guideline suggests that the safety functionality of autonomous control systems should take into account, amongst other things, an assessment of interactions between personnel (operational and maintenance) and the autonomous systems, and should consider "the impact of human interactions and behaviours on autonomous system performance" (p. 12). Considerations for operational practices are listed, including: operating team's technical knowledge, change management, interaction rules, and "human factors (e.g. response to system information or warnings, adherence to exclusion zones)" (p. 14). Maintenance safety considerations are also listed, including: recovery procedures in autonomous areas, isolation, calibration, and testing.

The Importance of ensuring work area design minimizes interaction between autonomous machines and manual vehicle and people is noted. Considerations here are listed as including: access controls, consumable resupply, loading, traffic management, mode changes, and placement of infrastructure.

British Columbia Ministry of Energy, Mines and Low Carbon Innovation (2022). BC Guideline for Safe Mobile Autonomous Mining (Guideline).

The BC guideline is an adaption of the Western Australian code of practice intended for use by mining operations in the Canadian province of British Columbia in the preparation of Autonomous Mining Project Management Plans for submission to the provincial government. This project plan must be "prepared by a qualified professional" and is required to contain many safety related elements including: a detailed risk assessment; a summary of the health and safety plan; a summary of system safety features; and interaction plan for human operated equipment; training program and competency assessment; process for investigating failures; and a summary of critical controls as identified in the risk assessment.

The guideline also summarises legislative provisions relevant to mines of the province specific to autonomous mining systems. These include the requirement for safe working procedures for autonomous equipment that address, for example: access to autonomous areas; procedures for working within an autonomous area; clearing of autonomous areas for restarting; switching modes; recovering a failed/stopped mobile autonomous equipment.

Another requirement noted in the guideline is that the legislation in the province (Section 6.19.1 of the Health, Safety and Reclamation Code for Mines in British Columbia) explicitly places responsibility on autonomous system supervisors for system safety viz.,

> "A person, who enters commands or inputs information into an autonomous or semi-autonomous system that governs the behavior of tracked or rubber-tired mobile equipment, must do so in a manner that ensures the safe operation of the equipment and that the system can maintain full control of the mobile equipment"

The explanatory notes provided in the guideline state:

> "Autonomous mobile equipment is controlled differently than conventional equipment. Conventional equipment has an operator behind the steering wheel who is responsible for maintaining control of the equipment (section 6.19.1 (1)). For an autonomous system, there can be a variety of people who are responsible for control of the system, including, but not limited to, individuals who survey the working area, restart stopped equipment, design the digital environment, assign tasks, or input commands to the system. *Any individuals who enter commands or input information into the system have a responsibility to ensure the system can maintain control of the equipment*." (p. 28). (Emphasis added)

It is not clear whether this responsibility extends to the system designers— for example, those who coded the software.

An additional obligation to prepare traffic control procedures placed on "the manager" by section 6.8.3 of the Health, Safety and Reclamation Code is noted to be applicable to autonomous mining operations. It is suggested that these procedures should include:

> "Rules for interactions between conventional and autonomous equipment; Autonomous operating area access and exclusion zones; Road, dumping and loading area design requirements and system limitations from manufacturer; and Priority rules." (p. 30).

Functional Safety Guidelines

Functional safety has historically formed a core component of efforts to ensure the safety of automated mining equipment. However, functional safety addresses the safety-related components of control system rather than the system as a whole, and such approaches do not adequately consider the role that humans play in system safety.

IEC 61508 Functional safety of electrical/electronic/programmable electronic safety-related systems

The IEC 61508 series of standards sets out methods for defining and achieving satisfactory performance of safety-related systems. Human factors issues related to the functioning of such systems receive only limited attention ie., as IEC 61508-1 explains:

> "Although a person can form part of a safety-related system (see 3.4.1 of IEC 61508-4) human factor requirements related to the design of E/E/PE safety-related systems are not considered in detail in this standard" (IEC, 61508-1, 1, note 2).

That noted, the IEC 61508 series of standards refers directly, or indirectly, to human factors issues in several places. IEC 61508-1 requires that:

> "The hazards, hazardous events and hazardous situations of the (Equipment Under Control) and the (Equipment Under Control) control system shall be determined under all reasonably foreseeable circumstances (including fault conditions, reasonably foreseeable misuse and malevolent or unauthorised action). This shall include all relevant human factor issues, and shall give particular attention to abnormal or infrequent modes of operation of the (Equipment Under Control)" IEC 61508-1, 7.4.2.3 (abbreviations expanded).

Similarly, it is noted in IEC61508-4 that the risk assessment of Equipment Under Control "will include human factor issues" (IEC61508-4, 3.1.9, Note 3). Little guidance is provided regarding how such consideration of such "human factor issues" is to be achieved. Although IEC 61508-7 suggests in section C.6.2 that a Software Hazard and Operability Study carried out by a "team of engineers, with expertise covering the whole system under consideration" should "consider both the functional aspects of the design and how the system would operate in practice (including human activity and maintenance)" in identifying hazards and risks.

In providing guidance regarding the application of parts 2 & 3, IEC 61508-6 (Annex A) defines potential failures of the safety system to include both physical faults and potential "systematic faults". The latter includes "human errors" made during the specification and design of a system that cause failure under some combination of inputs, or some environmental condition. The Annex further notes that:

> "Systematic failures cannot usually be quantified. Causes include: specification and design faults in hardware and software; failure to take account of the environment; and operation-related faults (for example poor interface). (IEC 61508-6, Annex A, 1, footnote 5)

Regarding the human-machine interface, IEC 61508-4 notes that:

> "a person can be part of a safety-related system. For example, a person could receive information from a programmable electronic device and perform a safety action based on this information, or perform a safety action through a programmable electronic device." (IEC 61508-4, 3.4.1, Note 5).

This note highlights the importance of considering human-machine interactions, and in particular the critical importance of effective interface design. Some information regarding operator interface design is provided in IEC 61508-3 where the software developer is directed to include consideration of "equipment and operator interfaces, including reasonably foreseeable misuse" in the definition of requirements for the system. (IEC 61508-3, 7.2.2.5, f)

IEC 61508-3 explains again that "human factor requirements related to the design of E/E/PE safety-related systems are not considered in detail in this standard", however suggests that, where appropriate:

- "An operator information system should use the pictorial layout and the terminology the operators are familiar with. It should be clear, understandable and free from unnecessary details and/or aspects;
- Information about the (Equipment Under Control) displayed to the operator should follow closely the physical arrangement of the (Equipment Under Control);
- If several display contents to the operator are feasible and/or if the possible operator actions allow interactions whose consequences cannot be seen at one glance, the information displayed should automatically contain at each state of a display or an action sequence, which state of the sequence is reached, which operations are feasible and which possible consequences can be chosen." (IEC 61508-3, 7.2.2.13, Note 2).

IEC 61508-7 refers to "User friendliness" as a relevant technique referenced in IEC 61508-2 that has the aim of reducing complexity during operation of the safety-related system. The technique is described as:

> "The correct operation of the safety-related system may depend to some degree on human operation. By considering the relevant system design and the design of the workplace, the safety-related system developer must ensure that:
>
> – the need for human intervention is restricted to an absolute minimum;
>
> – the necessary intervention is as simple as possible;
>
> – the potential for harm from operator error is minimised;

> – the intervention facilities and indication facilities are designed according to ergonomic requirements;
>
> – the operator facilities are simple, well labelled and intuitive to use;
>
> – the operator is not overstrained, even in extreme situations;
>
> – training on intervention procedures and facilities is adapted to the level of knowledge and motivation of the trainee user" (IEC 61508-7 B.4.2).

While these sections in parts 3 and 7 highlights the importance on human-interface design for the performance of the system, the guidance regarding the design of such interfaces is minimalist, and no guidance regarding the evaluation of such interfaces is provided.

ISO 19014 Earth-moving machinery — Functional safety

The ISO 19014 series of standards adapts functional safety methods for application to earth-moving machinery. The approach differs from IEC 61508 in that a "safety related system" is not defined, and the definition of "safety control system" employed does not include reference to humans. The method defined in ISO 19014-1 starts with identifying possible failure types for the machine control system but differs from IEC 61508 in not including explicit consideration of systematic failures. The method defined also appears to exclude any aspect of the system that is dependent on human reactions as safety-related parts of the control system. For example, section 5, "Requirements for immediate action warning indicators", reads:

> "The principles of this standard should also be applied to immediate action warning indicator intended to warn the operator of a possible hazard and requiring immediate action from the operator to correct and prevent such a hazard.
>
> These indicators shall not be designated as meeting a performance level as the output/diagnostic coverage is reliant on human reaction; indicators provide no control of the system and therefore cannot be labelled as safety-related parts of the control system" (ISO 19024-1, 5.1).

The inference is that human-machine interfaces are not addressed by the ISO 19014 series.

ISO 19024-1 suggests that participants in the development of a machine control system safety analysis should involve:

> "a cross functional team, for example, electronic or electrical development, testing or validation, machine or hydraulics design, operator, service, sales and marketing", (ISO 19024-1, 6.2).

There is no comment on the necessity for an understanding of human factors to undertake the assessment - despite requiring that the assessment of the controllability of a hazard take into consideration:

> "human reaction (e.g. panic, repeated command of function, etc.) and the capacity for the operator to react to the hazard and provide a means to enter a safe state" (ISO 19024-1, 6.5).

Similarly, ISO 19014-2 excludes consideration of awareness systems such as cameras that do not effect machine motion, and excludes audible warnings. ISO 19014-3 relates to environmental performance without relevance to human factors. ISO 19014-4 specifies general principles for software development and signal transmission requirements of safety-related parts of machine-control systems. No human factors input is required nor is any consideration of human-machine interface design principles or evaluation methods included.

ISO 21448 (2022) Road vehicles — Safety of the intended functionality

ISO 21448 provides a complementary approach to functional safety termed "safety of the intended function" that is designed for application to the complex sensors and processing algorithms used in road vehicles to maintain situation awareness. The aim is to avoid "unreasonable risks" due to performance limitations such as (i) the inability of the function to perceive the situation; (ii) lack of robustness of the function with respect to sensor input variations or environmental conditions; or (iii) unexpected behavior of the decision making algorithm; rather than system failures.

ISO 21448 Table 1 notes that reasonably foreseeable misuse; and incorrect or inadequate human-machine interface (HMI) (eg. user confusion, user overload, user inattentiveness) are potential causes of hazardous events that fall within the scope of the standard. Table 5 lists methods for identifying reasonably foreseeable visual as including analysis of use cases and scenarios, analysis of HMI, and "analysis of human capability to perform or switch between certain tasks". Measures for managing reasonably foreseeable misuse listed include "improving the HMI" (p. 41).

Informative Annex B provides guidance on analysing reasonably foreseeable misuse scenarios based on Human Factors Analysis and Classification System; and section B.4 outlines the use of Systems-Theoretic Process Analysis as a means of analysing the safety of complex systems.

Construction Mining Equipment Industry Group / Earth Moving Equipment Safety Round Table / International Council of Mining and Metals (2020) white paper - Functional safety for earth-moving machinery

A white paper compiled by a collaboration of manufacturers and mining company representatives discussed the application of functional safety approaches to the design of earth-moving equipment. It was noted that automation systems being introduced to earth-moving equipment include non-deterministic elements such as the complex sensors and processing algorithms for situation awareness addressed by ISO 21448 and that such systems cannot be analysed using the functional safety methods provided by IEC 61508 or ISO 19024. It was suggested that while traditional functional safety methods are concerned with identifying and preventing system failures, safety hazards can also occur in complex systems in the absence of failure and recommends the use of Systems Theoretic Process Analysis in addition to more conventional risk analysis methods focussed on system component failure. No explicit mention is made of human factors, and a figure provided suggests that Functional Safety and Human-Machine Interface are to be considered separate aspects of Systems Safety.

GMG (2020). GMG Guideline for Applying Functional Safety to Autonomous Systems in Mining.

The Global Mining Guidelines Group has published a "Guideline for applying functional safety to autonomous systems in mining". The guideline scope explicitly excludes non-deterministic elements of the system (eg., perception systems, artificial intelligence) however human aspects are referred to in the context of change management, where it is suggested that attention is required: "to confirm that the operations personnel are ready to adapt to the change" and that: "Everyone working at the operation should understand the risks of automation for the mine to be safe". (p. 3)

It is also recommended that risk assessments require:

> "A strong focus on the administrative controls on which the autonomous system is reliant. They should also consider how human behaviour changes as aspects of manned operation are replaced by the autonomous systems" (p. 4).

However, no guidance is provided regarding how this should be achieved.

A section on competency management is included that suggests identifying tasks to be undertaken and competency criteria for each, including "requirements that demonstrate knowledge, skills, experience, and behaviours" (p. 14). Again, no guidance regarding how these criteria might be derived or assessed is provided.

GMG (2021). System safety for autonomous mining.

Subtitled, "A White Paper to Increase Industry Knowledge and Enable Industry Collaboration on Applying a System Safety Approach to Autonomous Systems", the document notes that functional safety is not sufficient for non-deterministic systems such as those involving machine learning, and including systems reliant on human behavior. System safety is highlighted as an overarching process involving the use of a safety case. Descriptions of human-systems integration (based on Burgess-Limerick, 2020) and software safety management are provided for the education of industry.

Human systems integration in other industries

The standards and guidance materials available to assist mining operations implement automation are currently incomplete in that insufficient attention is paid to the integration of humans and technology within the resulting joint system. Human systems integration (HSI) refers to a set of systems engineering processes originally developed by the Defense industry to ensure that human-related issues are adequately considered during system planning, design, development, and evaluation. (Booher, 2003; Folds, 2015; INCOSE, 2015; 2023).

Defense HSI directives, standards, and guidelines

The USA Department of Defense Directive 5001.01 *The Defense Acquisition System* (2022a) requires human systems integration planning to begin early in the acquisition program lifecycle. Instruction 5000.95 (USA Department of Defense, 2022b) places responsibility on program managers and component capability developers to:

> "a. Plan for and implement an HSI program from initial user requirements through the program life cycle to system disposal, appropriate to the system's acquisition pathway. The goal is to:
>
> > (1) Optimize total system performance.
> >
> > (2) Reduce total ownership costs.
> >
> > (3) Ensure that the system is designed to be operated, maintained, and supported while providing users with the ability to effectively complete their mission(s).
>
> b. Perform, document, and manage program and systems human-centered design considerations and readiness risks through trade-off analyses among the HSI domains. The trade-off analyses will ensure human performance data systematically informs and facilitates total system performance in both materiel and non-materiel solutions during SE activities.
>
> c. Ensure that DoD Component HSI subject matter experts (SMEs) and HSI practitioners are engaged with working groups tasked with the development and review of program documents that:
>
> (1) Manage HSI planning.
>
> (2) Report on HSI program and HSI domain level execution to the OSD and DoD Component heads assigned responsibilities in Section 2 throughout the course of the program.
>
> (3) Inform program managers on acquisition program decisions."
>
> (USA Department of Defense, 2022b; p. 6)

Instruction 5000.95 further requires component capability developers and program managers to undertake a combination of risk management, engineering, analysis, and human-centered design activities including:

- the development of a human-systems integration management plan
- taking a human engineering design approach for operators and maintainers
- task analyses
- analysis of human error
- human modelling and simulation
- usability and other user testing
- risk management throughout the design life-cycle
- developing a training strategy

While Instruction 5000.88 "*Engineering Defense Systems*" (USA DoD, 2020) obliges the lead systems engineer to:

> "use a human-centered design approach for system definition, design, development, test, and evaluation to optimize human-system performance … Conduct frequent and iterative end user

> validation of features and usability … (and) … ensure human systems integration risks are identified and managed throughout the program's life-cycle…" (p. 23)

Seven HSI domains are defined by the Department of Defense instruction: human factors engineering, personnel, habitability, manpower, training, safety and occupational health, and force protection and survivability. In the human factors engineering domain, the program manager is required to ensure that design considerations addressed include: the design and layout of work environments; human-machine interfaces; design for maintenance; automation; and minimising system characteristics that require excessive cognitive, physical or sensory skills, or workload-intensive tasks. The personnel domain primarily involves identifying the knowledge, skills and abilities of available personnel, while manpower considers the requirements of the system. Activities in the training domain include training effectiveness evaluations to develop options for individual, collective and joint training activities including simulation-based training. Habitability concerns the requirements for the physical environment; the safety and occupational health domain focusses on prevention of fatality and injury, and minimising health risks; and the force protection and survivability domain concerns the mitigation of external treats.

The processes described ensure that human considerations are integrated into the system acquisition process. The importance of including human systems integration subject matter experts throughout the acquisition program is made explicit. It is notable that, in contrast to the mining automation guidance, safety is considered to be a subset of human systems integration.

Additional guidance is provided within the "*Human Systems Integration Guidebook*" (USA Department of Defense, 2022c). The guidebook emphasises the importance of considering and analysing interactions and trade-offs between the domains; and of taking a total systems approach. This approach includes attention to:

> "equipment and software as well as people who operate, maintain, and support the system (including those involved with the creation and implementation of training requirements and training devices, the operational and support infrastructure, etc.)" (USA DoD, 2022c, p. 5)

The guidebook notes that:

> "The payoff for using HSI in all acquisition planning is enormous. Cost benefits include improved use of manpower, reduced training costs, reduced maintenance time, and improved user acceptance, all of which decrease overall program costs. Improved operational availability and performance can result in fewer errors, and improved design trade-off decisions can reduce life cycle costs and decrease the need for redesigns and retrofits." (USA DoD, 2022c, p. 6).

The earlier "Air Force Human Systems Integration Handbook" (USA Air Force, 2009) suggests that HSI typically comprises 2.0-4.2 per cent of the total system acquisition cost and leads to a return on investment of between 40-60 times the investment.

The United Kingdom Ministry of Defence refers to 'Human Factors Integration', rather than human systems integration, however the intent conveyed by Defence Standard 00-251: "*Human Factors Integration for Defence Systems*" (UK Defence Standardisation, 2015) is similar. The formal requirements are set out in Joint Service Publication 912 (UK Ministry of Defence, 2021) "*Human Factors Integration for Defence Systems*". Here the domains are identified as: Personnel; Training; Human Factors Engineering; System Safety and Health Hazards; and Social & Organisational.

Part 1 of Joint Service Publication 912 requires that the following "shall be fully pursued to achieve satisfactory outcomes" in all acquisition projects:

> "a. ensure that all people-related Risks, Assumptions, Issues, Dependencies and Opportunities (RAIDO) are identified and managed from the very outset of a project, and throughout the rest of life cycle.
>
> b. ensure that all Human Factors Process Requirements (HFPRs) are specified, thereby assuring that HFI processes are properly and adequately undertaken.
>
> c. ensure that Human Factors System Requirements (HFSRs) are specified, thereby assuring that people-related technical aspects of the Solution are properly and sufficiently addressed (based on the identified RAIDO).

> d. ensure that a human-centred design approach is adopted, involving the End Users in system and equipment design and evaluation.
>
> e. ensure that established Human Factors principles, accepted leading practice, and suitable methods, tools, techniques, and data are used.
>
> f. ensure that the HFI programme is designed to align and integrate effectively with the project life cycle.
>
> g. ensure that people-related considerations of the Solution undergo formal scrutiny, assessment, and acceptance."

Part 2 of JSP 912 provides guidance in achievement of these goals. It is noted that failure to consider humans can increase the risk of accidents, increase costs (including training costs), and reduce performance. Human Factors Integration activities are defined to include: analysis activities (requirements analysis; task analysis; human performance modelling; human reliability analysis; training needs analysis); design activities (application of standards; modelling, prototyping, human computer interface design, workplace design, training design, organization design); and test and evaluation activities (assessment of compliance, manual handling assessment, safety case, assessment of procedures, training evaluation).

Aviation and Space Human Systems Integration

Predating the development of human systems integration as a formal discipline, the USA Federal Aviation Administration (FAA) Order 9550.8 (FAA, 1993) required that:

> "Human factors shall be systematically integrated into the planning and execution of the functions of all FAA elements and activities associated with system acquisitions and system operations".

This was required at the earliest opportunity to achieve increased performance and safety, and decreased lifecycle staffing and training costs. The FAA (2016) standard HF-STD-004a "*Human Factors Engineering Requirements*" describes human factors activities expected to be undertaken by vendors and requires that the activities to be conducted are described in a Human Factors Program Plan including: tasks to be performed, human factors milestones, level of effort, methods, design concepts, and human factors input for the test and evaluation plan. Human factors collaboration with other disciplines including safety, training, systems engineering, and personnel selection is required.

The USA National Aeronautics and Space Agency (NASA) requires human systems integration to be implemented and documented in a Human Systems Integration Plan. The plan identifies the steps and metrics to be used throughout a project life-cycle, and the methods to be undertake to ensure effective implementation and maximise system performance and safety while reducing risks and life-cycle costs. A "*Human Systems Integration Handbook*" (NASA, 2021) provides guidance.

Human systems integration is defined by the NASA handbook as the:

> "interdisciplinary integration of the human as an element of a system to ensure that the human and software/hardware components cooperate, coordinate, and communicate effectively to successfully perform a specific function or mission".

The system is defined to include hardware, software and humans, as well as data and procedures. The human systems integration plan must be established early in program planning and the processes undertaken iteratively, considering all people who interact with the system throughout the entire life-cycle, and collaborating across multiple domains.

While the origins of the discipline in defense are noted, the relevant domains for application to aviation and space are defined by NASA as:

- Human Factors Engineering – Designing and evaluating interfaces and operations considering human performance characteristics. Activities in this domain include analyses of tasks and human performance capabilities and limitations, and evaluation of design alternatives.
- Operations – Life-cycle engagement of operational considerations into design for human effectiveness for operations and maintenance crews. Particular attention is directed to the design of interactions between human and automated components of the system.

- Maintainability and Supportability – Designing for simplified maintenance to reduce maintenance errors, as well as increasing maintenance efficiency (reduced training and manpower) and system availability.
- Habitability and Environment – Design of living and working environments including lighting, ventilation, noise, temperature, and environmental health.
- Safety – Life-cycle consideration of safety to reduce risks. Activities in this domain include systematic analyses of risks and development of system designs that minimise these risks. Attention is directed to both safety and health hazards.
- Training – Design and implementation of training to equip all humans in the system with the knowledge, skills and attitudes required to accomplish mission tasks. It is noted that training planning should occur throughout the project life-cycle because design decisions will impact the extent and nature of training required. Analyses of training needs provides input to the evaluation of design alternatives.

Human systems integration is defined to include analysis, design and evaluation of requirements, concepts, and resources across the domains.

Effective application of human systems integration is understood to result in improved safety and health, increased user satisfaction and trust, increased ease of use, and reduced training time; all leading to higher productivity and effectiveness. Conversely, NASA identifies failure to apply human systems integration as increasing risks of major accidents as well as minor incidents, greater training requirements and higher costs including those associated with redesigns and maintenance. The NASA handbook provides a series of case studies providing examples of the value of effective human systems integration, and examples of the consequences of failing to do so.

The introduction of automation or new technology should include a human-centered design process that, to paraphrase NASA standard 3001 (2015), encompasses at a minimum:

- Concepts of operation and scenario development
- Task analyses
- Function and role allocation and definition (between humans and automation, and among humans), including training and competency assessment needs analysis
- Iterative conceptual design and prototyping
- Empirical testing, e.g., human-in-the-loop simulation
- Monitoring of human-system performance during operation

Similarly, the European Organisation for the Safety of Air Navigation which develops standards for Air Traffic Management (ATM) systems and services provided principles for the integration of human factors and ergonomics (HF/E) in system design with a particular emphasis on the achieving the anticipated benefits of automation in "*Human Factors Integration in ATM System Design*" (Eurocontrol, 2019). These are summarised as:

> "1. Build **joint design teams** and do not treat HF/E as a mandatory add-on
>
> 2. Make a coherent **user-centred-design rationale** your HF/E product
>
> 3. Strive for a short, iterative **user-centred design process**
>
> 4. Derive **objective HF/E criteria** instead of relying on user opinions
>
> 5. Evaluate as early as possible with the help of **prototypes**
>
> 6. Select appropriate **conditions for evaluation**: Evaluate day-to-day operations as well as critical situations
>
> 7. Support the **problem-solving** process during implementation by facilitating trade-offs
>
> 8. Do a proper **problem setting** in the first place whenever possible to understand your actual problem and the underlying mechanisms and needs
>
> 9. Be ready to participate in strategic decisions and introduce a **purpose-orientated view of Technology**" p. 3 (emphasis in original)

Rail

HCD and HSI approaches are well-embedded in engineering design processes utilized by rail operations. In USA rail, the term 'Human Systems Integration' is employed, whereas in Australian rail 'Human Factors Integration' is more common: however the processes in both countries are very similar. For example, AS7470 (Standards Australia, 2016) was specifically prepared to support Human Factors Integration (HFI) into the engineering design process within the Australian Rail Industry. This includes the requirements for organizations conducting or procuring engineering design activities, services or products to:

- incorporate Human Factors within their engineering design processes,
- ensure their products comply with the generic Human Factors requirements in the standard,
- use the HFI process to identify the specific Human Factors requirements of the system or asset being designed, procured or modified.

The aim of the requirements specified in AS7470 is to optimize overall system performance through the systematic consideration of human capabilities and limitations as inputs to an iterative design process. Adequate integration of Human Factors in all phases of a system's development lifecycle ensures its safety, performance and fitness for purpose. Equally, the aim of the HFI process is to identify then mitigate and prevent Human Factors related risk and ensure that human-system interactions are optimised for system performance and safety. Incorporating HFI into the engineering design process also facilitates a high level of system acceptance amongst end users.

The USA Federal Railroad Administration defines HSI as a "systematic, organization-wide approach to implementing new technologies and modernizing existing systems." It combines methods, techniques and tools designed to emphasise the central role and importance of end-users in organizational processes or technologies. HSI here refers to efforts to increase safety, manage risk, and optimize performance of those who work in socio-technical rail systems. HSI considers the human role (both individuals and teams) as part of a system that includes tasks, technologies, and environments. HSI ensures that characteristics of people are considered, and accounted for, throughout the design and development of systems. HSI guidance has been provided for the acquisition of complex railroad technologies (Melnik et al., 2018).

Human systems integration for mining system acquisition

Human systems integration incorporates human-centered analysis, design, and evaluation within the broader systems engineering process. That is, human systems integration is a continuous process that should begin during the definition of requirements for any automation project, continue during system design iterations, and throughout commissioning and operation to verify that performance, safety, and health goals have been achieved.

A framework for human systems integration in mining is presented in Figure 26. Six domains relevant to the introduction of automation or other complex technologies in mining are defined: staffing; personnel; training; human factors engineering; safety; and health.

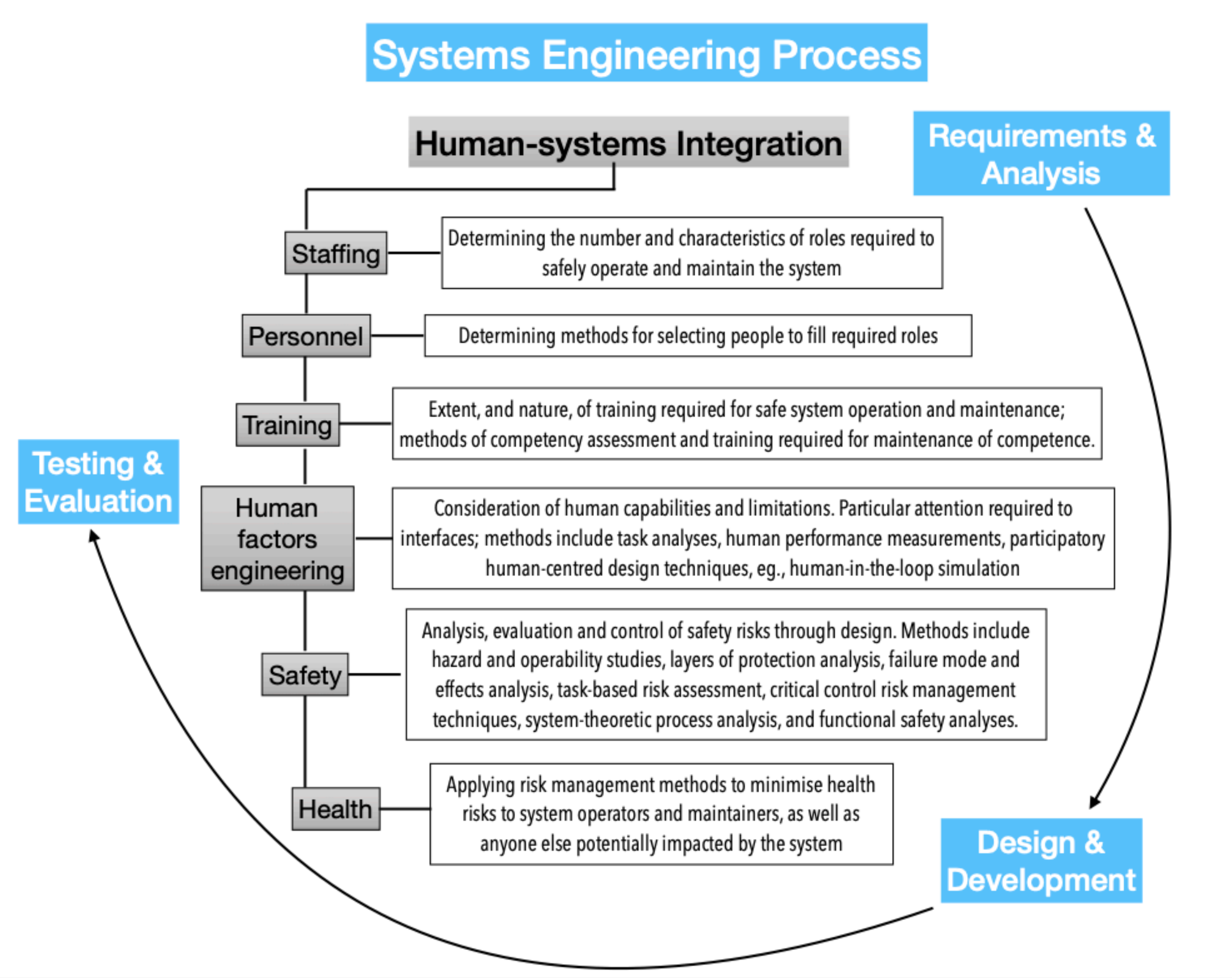


Figure 26: Human systems integration for mining automation. (Burgess-Limerick, 2020)

"*Staffing*" concerns decisions regarding the number, and characteristics, of the roles that will be required to operate and maintain the joint human-automation system. Decisions here may well require consideration of the outcomes of investigations in other domains particularly where workload issues are involved.

The "*personnel*" and "*training*" domains concern, respectively, the related issues of the characteristics of the personnel who will be selected to fill those roles; and the extent and methods of training, and competency assessment, involved in preparing personnel to obtain and maintain competencies (knowledge, skills, and abilities) required for safe and effective operation and maintenance of the joint human-automation system. Rather than decreased, training requirements for operators interacting with highly autonomous systems are likely to be increased to ensure the operation of the automation is fully understood. For example, automated system controllers need to understand: system hazards and logic, and reasons behind safety-critical procedures; potential results of overriding controls; and how to interpret feedback. Skills for solving problems and dealing with unanticipated events are also required. Emergency procedures must be over-learned and frequently practiced.

Instructional system design models (Gordon, 1994) exemplify the application of human factors principles to training. In essence, such models involve front-end analysis steps (analysis of the situation, task, equipment interface, trainees, training needs, and resources, leading to definition of the training functional specifications), followed by design and development steps (training concept generation, training system development and prototyping, and usability testing) and system evaluation steps (determining training evaluation criteria, collection and analysis of these data, and subsequent modification of the training if indicated).

The front-end analysis (or training needs analysis) step in training design is critical. In particular, a comprehensive analysis of the tasks performed by equipment operators and maintainers is required before the training needs and associated functional specifications can be determined. The aim of the task analysis is to describe the knowledge, skills, and behaviors required for successful task performance, and identify the potential sources and consequences of human error. This task analysis would typically involve interviews with experts, reviews of written operating and maintenance procedures, and observations of equipment in use. It should include consideration of the information required by equipment operators and maintainers and how this information is obtained, the decision-making and problem-solving steps involved, the action sequences, and attentional requirements of the task. The task analysis should be conducted systematically, and well documented, to provide a solid foundation for the design of training and to provide a template for future training needs analyses.

An extension of the task analysis to include a cognitive task analysis may be justified for more complex task–equipment interfaces. Cognitive task analysis seeks to understand the cognitive processing and requirements of task performance, typically through the use of verbal protocols and structured interviews with experts. The outcomes of a cognitive task analysis include identification of the information used during complex decision making, as well as the nature of the decision making. The cognitive task analysis can also reveal information which will underpin the design of training and assessment. Again, the outcome of a cognitive task analysis may include identification of design deficiencies which should be fed back into the design process.

The results of the task analysis are also used in the second phase of training design to define the actual contents of the training program, as well as the instructional strategy required. Regardless of the content of the training (the competencies required), or the methods employed, most effective instructional strategies embody four basic principles:

- The presentation of the concepts to be learned
- Demonstration of the knowledge, skills, and behaviors required
- Opportunities to practise
- Feedback during and after practise (Salas & Cannon-Bowers, 2021).

An initial training design concept is typically refined iteratively through usability evaluation of prototype training models, until a fully functional final prototype is considered ready for full-scale development. Issues to be considered include the introduction of variation and the nature and scheduling of feedback. A compelling case has been presented (Schmidt and Bjork, 1992) to suggest that variation in the way tasks are ordered and in the versions of the tasks to be practised is important, and that less frequent feedback should be provided. Whilst immediate performance may be reduced, retention and generalization are enhanced as a consequence of the deeper information processing required during practice.

Evaluation of the consequences of training is also an essential and non-trivial step, and the task analysis aids in determining the appropriate performance measures to be used in evaluation (or competency assessment). A valid training evaluation requires careful selection of evaluation criteria and measures (closely connected to the task analysis results) and systematic collection and analysis of data. The use of simulation is a promising method for allowing trainees to be exposed to rare events, as well as for competency assessment.

"*Human-factors engineering*" encompasses the consideration of human capabilities and limitations in system design, development, and evaluation (Horberry et al., 2011). In the automation and technology context, this is particularly important in the design of interfaces between people and automated components. While the use of human engineering standards (eg., MIL-STD-1472H) may be useful, they are not sufficient. Prescriptive standards are often too general to be helpful in specific situations, they do not address tradeoffs that may be necessary, and they reflect the technology of the time at which they were written.

Other methods employed in human factors engineering include task analyses such as those described in the previous section, and human performance measures (e.g., workload, usability, situation awareness), as well as participatory human-centered design techniques (Horberry et al., 2018). Human-in-the-loop simulation allows analysis of the activities undertaken to achieve tasks during the design phase (INCOSE, 2023).

ISO 9241 provides principles for human-centered design of computer-based interactive systems which will be relevant to many automation projects:

> " a) The design is based on an explicit understanding of users, tasks and environments
> b) users are involved throughout design and development
> c) the design is driven and refined by user-centred evaluation
> d) the process is iterative
> e) the design addresses the whole user experience
> f) the design team includes multidisciplinary skills and perspectives". (ISO, 2010; p. 9)

Use-cases, that is, a description of a task performed by a person interacting with a system and the system responsibilities in accomplishing that task (cf. Constantine & Lockwood, 2001) provide a starting point for user interface design.

The "*safety*" domain includes consideration of safety risks such as those identified in ISO 17757. Relevant methods include traditional risk analysis and evaluation techniques such as hazard and operability studies, layers of protection analysis, failure modes and effects analysis, as well as functional safety analyses, and systems-theoretic process analysis (STPA).

STPA in particular may be useful for analysis of complex systems involving automated components because both software and human operators are included in the analysis (Leveson & Thomas, 2018). STPA is a proactive analysis method that identifies potential unsafe conditions during development and avoids the simplistic linear causality assumptions inherent in traditional techniques. Safety is treated as a control problem rather than a failure prevention problem. Unsafe conditions are viewed as a consequence of complex dynamic processes that may operate concurrently. STPA also includes consideration of the wider, dynamic, organizational context in which the automated system is situated. STPA has been successfully used during the development of automated bulldozers (Beasley & McAree, 2020) and automated haulage (Baillio, 2020). Other systems-based analysis techniques (eg., SAfER) may also be useful (Hassall, et al., 2014; 2022)

The "*occupational health*" domain encompasses the use of risk management techniques, and task-based risk assessment in particular (e.g., Burgess-Limerick et al., 2012), to ensure that the system design minimises risks of adverse health consequences to system operators and maintainers, and indeed, anyone else potentially impacted by the system activities. These analyses should encompass all operational and maintenance activities associated with the autonomous component or system.

One health issue associated with the introduction of autonomous systems to mining is the potential impact on the physical and mental health of control-room operators tasked with interacting with autonomous systems. Stress associated with high (or low) cognitive workloads, potentially combined with reduced social interactions and low control of workload, and/or production pressures, may lead to adverse mental health consequences.

An overall focus on human systems integration includes consideration of interactions and potential trade-offs between decisions made in different domains. For example, decisions regarding automation and interface complexity may influence personnel characteristics and training requirements, as well as the anticipated number of people required for system operation and maintenance; while issues highlighted during the safety analysis may well lead to additional human factors engineering work to reduce risks.

Implementation of HSI during mining system acquisition

Guidance provided by Melik et al. (2018) for the acquisition of complex railroad technologies has been adapted in the following section for the acquisition of new mining technologies. Although the stages of systems engineering are presented sequentially, as Folds (2015) notes, the reality is that iterative loops occur both within stages and between stages. While the results of evaluations conducted during design and development will certainly influence subsequent design iterations, they may also feedback to changes to requirements, or even result in changes to the concept of operations.

Analysis

The initial stage of the systems engineering process is analysis. Human-centered analysis activities conducted as part of human systems integration address the following:

- Concept of operation — What are the goals of the system and, in particular, what are the anticipated operational and maintenance roles that people will play? Who will these people be? What knowledge and skills will they have? What diversity is anticipated? Are there other people inside or outside the system that should be considered?
- Contexts — What is the range of operational contexts and use cases? Are there different modes of operation? What range of environmental conditions is anticipated?
- Tasks — how will functions be allocated within the system? What physical tasks will people need to perform? What monitoring or decision-making tasks need to be undertaken? What current tasks will no longer be undertaken or altered? What are the critical tasks that are performed by people? A variety of task analysis techniques may employed depending the nature of the tasks. Similarly, analyses of workload and situation awareness are likely to be appropriate.
- Known challenges / lessons learned — Are there known human performance concerns based on experiences with similar systems in the same or other industries? What can be learned from previous incidents or near-misses?
- Safety and health — What hazards may be present? How could adverse safety or health outcomes occur? What errors could people make and what would be the consequences? How can the potential for detection of both human and technological errors, and recovery from errors, be increased? What critical controls are required to prevent or mitigate adverse safety or health outcomes?
- Tradeoffs — Are there tradeoffs between human systems integration domains that need to be evaluated? Are there tradeoffs between the human systems integration domains and other systems engineering elements (e.g., cost) that require examination?

Requirements

The output of these analyses leads to human systems integration requirements that inform subsequent system design and development. Potential requirements include:

- Information — What information needs to be received by people in the system to maintain situation awareness? How should the information be presented to best support decision making?
- Control — What controls and modes of interaction with the system are required?
- Communication — What communication channels are required inside and outside the system? What methods of communication should be provided?
- Physical environment — What physical workstation designs are required, eg., layout, lighting, visibility, reachability? How will human diversity be accommodated?
- Selection and Training — How will the people in the system be selected? What training (initial and ongoing) will be required? How should the training be undertaken? How will competency be assessed and reassessed?

Design

Based the explicit understanding of users, tasks and environments, a human-centered design and development process involving users is undertaken by a multidisciplinary team including human factors expertise. The process is iterative, likely involving the design and testing of prototypes of increasing fidelity, and likely to involve human-in-the-loop simulation.

Design and development outcomes will include:

- Work environment — Design of physical environments to maximise performance, as well as health and safety. Human engineering standards may be particularly relevant to physical design.
- Software and interfaces — Design of the overall software architecture, as well as the interfaces through which information is received by humans, and through which input is given by humans, to ensure efficient and safe performance under normal and abnormal conditions.
- Training — Design of the curriculum, training methods, and competency assessments.
- Documentation — Developing readable, understandable, and usable procedures, training manuals and related operations and maintenance documentation that reflect "work-as-done" rather than "work-as-imagined".

Testing and evaluation

User-centered evaluation occurs throughout the entire systems engineering process, as well as at final system validation. Testing and evaluation activities include:

- Planning — Human systems integration issues should be incorporated into the overall systems engineering testing and evaluation program.
- Evaluation of prototypes — Users representing the diversity of the intended workforce participate in evaluations of prototypes of increasing fidelity. Both physical and virtual simulations may be useful, human-in-the-loop simulation even more so.
- Human engineering discrepancy resolution — Aspects of the design that do not meet requirements during the iterative evaluations are systematically identified and tracked. Corrective actions are proposed and implemented.
- Final validation — Each requirement requires evaluation in the final system validation. Evaluation scenarios include the contexts and use cases identified during the analysis stage. Data collected will include process measures (eg., workload and situation awareness) and outcome measures, as well as user evaluations.

Human-systems integration program plan

During the preparation of proposals to implement any new technology at mines, and particularly if automated components are involved, vendors should be required to submit an human systems integration program plan that details the human systems integration work that will be performed in collaboration with the purchaser; how it will be done; and by whom.

A human-systems integration program plan should include:

- Overview — An overview of the proposed system; preliminary concept of operations, associated human roles, and operational environment; experiences with predecessor systems.
- Organizational capabilities — Summary job descriptions and the qualifications of key human-systems integration practitioners within the vendor.
- Program Risks — A discussion of how human-systems integration risks will be identified and addressed.
- Human systems integration activities — The specific human systems integration activities that will be performed by the vendor in collaboration with the purchaser to address each of the domains of human systems integration during system analysis, design, and evaluation. Identification of who will undertake these activities.

Human systems integration schedule — A milestone chart identifying each human systems integration activity, including key decision points, and their relationship to the program milestones.

Conclusions & Recommendations

Conclusions

Considerable benefits of removing miners from exposure to health and safety hazards through automation are evident. Removing underground workers from exposure to rock fall, explosion, fire, dust, and cumulative musculoskeletal injury hazards are particularly beneficial. The introduction of autonomous haulage at surface mines reduces safety and health hazards experienced by truck operators, and reduces collision risks for operators of other equipment on site. Removing operators from surface drill rigs and dozers has both safety and health benefits.

At the same time, automation provides increased productivity through increased consistency of equipment operation and increased equipment utilization rates arising, for example, from the ability to operate underground equipment through blasting and shift-changes. Ensuring equipment operation always remains within specifications reduces wear.

These productivity gains may take time to achieve at a site, and a willingness on the behalf of management to accept temporarily reduced output during the commissioning of the new technology is required. The increasing use of automated components within the mining system has potential to allow safe and economically viable access to the deeper and lower grade mineral deposits essential to meet projected demands for minerals. In summary, there are both economic, and safety and health imperatives for the USA mining industry to implement automated mining equipment.

That said, the implementation of automated mining equipment introduces new potential failure modes. Successfully implementing change of this magnitude requires a human-centered design process that involves all people who will be impacted by the changes. While standards and guidelines have been provided to assist the implementation of automation in mining, the extant documents are incomplete in that insufficient attention has been paid to the integration of humans and technology within the resulting joint systems.

Recommendations to industry

Mine operators implementing autonomous mining equipment should take steps to understand and manage the failure modes associated with automation that have potential adverse safety and health outcomes. These failure modes include:

- *Software shortcomings.* Verifying that software is trustworthy is difficult. Testing can only reveal the presence of flaws rather than prove the absence of errors. This is particularly true if machine learning is involved. Mine operators who have implemented autonomous machinery described spending considerable time verifying the operation of software updates prior to release.
- *Communication technology disruption.* Autonomous mining systems are dependent on continuous digital communications. Considerable effort is typically required to ensure the required networks are in place and maintained. Loss of network connectivity is a common cause of lost productivity and at least one potentially serious incident has occurred in which a communication interruption was implicated.
- *Cyber security breach.* Breaches have occurred and this is a risk that will increase as autonomous systems become more prevalent. Continuous attention to network security is warranted given the potential damage that a malicious actor could achieve. The human aspects of cyber security also require attention.
- *Unauthorised access to autonomous zones*. Incidents have occurred at surface mines where vehicles not fitted with site awareness systems have accessed active autonomous zones without escort, despite the access control systems in place. In the underground context, incidents have occurred in which automated equipment was activated in an isolated autonomous area with multiple faces while persons were located in the area.

- *Loss of manual skill.* Machine operators' manual skills will deteriorate if not practiced. Whether this is a concern will depend on whether the system concept of operation includes reinstating manual operation at any time, and in what circumstances.
- *Over-trust.* People working in the vicinity of autonomous systems are likely to change their behavior to take advantage of the perceived safety features of the system. Driving a light vehicle through an intersection in front of an autonomous truck, trusting that the truck will take evasive action, is an example. Ensuring that people working with autonomous components have an accurate understanding of the system's capabilities and limitations, and the physical constraints, is important. So is supervision, monitoring, and enforcement of safety related procedures such as hierarchy road rules.
- *Input errors.* Where human controllers are responsible for entering information into the system there is potential for error. The probability of such errors is reduced by careful software and interface design. Where remote control is included in the concept of operations, the design of the workstation controls should take into account the possibility of mode errors, and ensure that directional control-response compatibility is maintained.
- *Inadvertent mode changes.* Whenever equipment can be operated in different modes there is potential for inadvertently switching between modes. This includes switching between autonomous and manual modes.
- *Complex interactions.* Systems including autonomous components may give rise to unpredicted adverse consequences even when all components function as intended. Several examples of such incidents have occurred. The use of systems-based risk analysis techniques in addition to hazard or failure-based methods is required to identify and control such potential outcomes.
- *Sensor limitations.* Sensors have limitations that can result in inaccurate or insufficient data being received by the system. These limitations require analysis and management.
- *Lack of system awareness of environment.* Removing operators from direct perceptual contact with the operating environment creates the potential for loss of awareness of the environment. One example that has lead to incidents is wet roadways leading to loss of traction. Another example is the difficulty encountered by autonomous underground drilling equipment in poor ground conditions.
- *Loss of situation awareness.* Several incidents have occurred in which the operators of equipment being operated manually in the vicinity of autonomous haulage have failed to predict the movements of the autonomous haulage, despite being provided with a system interface intended to provide this information. Incidents have also occurred in which an unfolding situation has not been identified by a control room operator despite, for example, video feeds providing the necessary information. These incidents highlight the difference between information being available and being perceived, and hence the critical importance of interface design to assist people within the systems understand current system states and accurately predict the likelihood of future states.
- *Distributed situation awareness challenges*. A related issue is that in many systems there will be no individual who possesses all the information required to maintain overall situation awareness of the whole system. Instead, the situation awareness is distributed across the people and technology within the system. Maintaining accurate distributed situation awareness is a dynamic and collaborative process requiring moment-to-moment interaction between team members and technology that can be hindered by limitations in system, or interface, design.
- *Communication difficulties.* Communication between team members is critical. Difficulties associated with technology limitations, or cognitive overload caused by multiple simultaneous communication channels, can impede performance with potential safety or health consequences. Non-technical skills, and the absence of psychosocial conflicts, are also required to ensure effective team-work.
- *Workload.* Potential exists for control room operators or others impacted by the introduction of automation to be overloaded, with consequential risks of errors, and adverse health

consequences. The workload of all people within the system is a key aspect for consideration in system design.

- *Musculoskeletal injury risk factors.* Long duration sedentary work with few breaks combined with static or awkward postures and/or excessive pointing device use, especially if accompanied by psychosocial risk factors such as high cognitive workload, time pressure, and/or conflict with peers or supervisors may create a situation in which musculoskeletal injury risk is high.

Effective risk management requires analysis of these potential unwanted events during system design. The analyses undertaken should include task-based risk assessments involving a range of operators and others effected by the system, and systems-based techniques; in addition to conventional hazard based risk analysis techniques. As far as possible, the risks should be reduced during system design. Residual risks need to be understood by mine management to allow effective controls to be devised, implemented, and monitored.

Human systems integration processes adapted from other industries should be implemented during acquisition of automated mining equipment and a human systems integration program plan should be required of technology vendors during procurement.

Issues of particular importance include the design of interfaces to maintain situation awareness, and the training of people who will undertake new roles. The extent of training required for all those impacted by the technology should not be under-estimated, and will likely be increased compared to previous roles. Ongoing training and competency assessment will be required as the systems are modified. Ensuring that sufficient numbers of trained control room staff are available to the industry is critical for both productivity and safety and health.

Research recommendations

There appears to be a greater reluctance for USA mining operations to pursue the implementation of autonomous mining equipment than observed in Australia, Chile, Canada and Sweden. It may be that risk-based legislative frameworks provide a more fertile ground for the implementation of innovations such as automation than prescriptive legislative approaches.

Efforts to understand this apparent reluctance are underway. LaTourrette & Regan (2022) examined barriers to the implementation of new technologies in underground coal mining and suggested that USA mine operators exhibit a "general resistance to change". It is not known whether this is specific to underground coal mines, or more generally true of US mining industry. However, it was suggested by equipment suppliers that this resistance persists even in the face of evidence for economic and productivity benefits.

In a presentation to the Mine Automation and Emerging Technologies Health and Safety Partnership, Luxberger (2023) presented preliminary findings from four workshops held across the USA with diverse mining groups. In each case, the workshop participants nominated "economics" as being a greater barrier to the implementation of automation than "regulation", "technological readiness", "corporate willingness" or concerns about "social license". This being the case, further targeted investigation and promotion of the productivity benefits associated with the implementation of automation in mining may be the key to unlocking the willingness of USA mining operations to embrace the introduction of automation and achieve the associated safety and health benefits.

As mining operations in the USA do implement autonomous mining equipment there will be opportunities for researchers to engage with these sites and document both the implementation processes, and outcomes for productivity, as well as safety and health. In concert with such case studies, an opportunity exists to combine conventional hazard based analysis methods with task-based methods and systems-based methods to gain a holistic understanding of automation risks (Hassall et al, 2022). This will be particularly important as the use of machine learning becomes more prevalent and "isolation-free" autonomous equipment is introduced underground.

The importance of interface design has been highlighted across all mining automation installations. Human-in-the-loop simulation research has potential to identify opportunities for improving current interface designs, with a particular focus on maintaining distributed situation awareness, improving decision making, and reducing control-room operator workload.

Research that investigates methods of achieving optimal teamwork and decision making in the context of autonomous mining systems is justified.

Research is needed to better understand the organizational culture attributes that support and allow a smooth transition to automated systems. This research should address technology acceptance/resistance, information overload, and the potential for change in situational awareness.

Several of the companies included in the study highlighted the potential for skill decay as important. Skill development or re-skilling as well as skill maintenance were also identified as essential. These related issues that deserve investigation include the design and evaluation of training and competency assessment methods for those who will be impacted by the introduction of automation. The optimal use of simulation; how team-training should be undertaken to maximise distributed situation awareness; and how non-technical skills should be trained and evaluated in the context of such teams, are all potential topics.

References

Albus, J. Quintero, R., Huang, H-M & Roche, M. (1989). *Mining automation real-time control system architecture standard reference model (MASREM).* NIST Technical Note 1261 Volume 1.

Androulakis, V., Sottile, J., Schafrik, S., & Agioutantis, Z. (2019). Elements of Autonomous Shuttle Car Operation in Underground Coal Mines. *Proceedings of the 2019 IEEE Industry Applications Society Annual Meeting*, pp. 1-7.

Atkinson, G. (1996). *Automated mining machine safety investigation*. Unpublished MSc thesis. McGill University.

Baillio, B. (2020). ASI Experience with STPA. Unpublished document, ASI Mining.

Bauer, E.R., Babich, D.R., & Vipperman, J.R. (2006). *Equipment noise and worker exposure in the coal mining industry*. NIOSH IC 9492.

Bhattacharya, J. (2020). Wireless network capacity and capability is a pre-requirement for implementation of automation and other technologies in open-pit mining. *Journal of Mines, Metals and Fuels*, *68,* 152–152.

Beasley, P. & McAree, R. (2020) *SATS Automated Mission Planning*. ACARP project C27063, Current projects report, February 2020.

Bellamy, D. & Pravica, L. (2011). Assessing the impact of driverless haul trucks in Australian surface mining. *Resources Policy, 36*, 149-158.

Benlaajili, S., Moutaouakkil, F., & Chebak, A. (2021). Infrastructural requirements for the implementation of autonomous trucks in open-pit mines. *Proceedings of the VIth International Innovative Mining Symposium* E3S Web of Conferences 315, 03009.

BHP (2022a). BHP unveils world-first automated ship loaders. https://www.bhp.com/news/media-centre/releases/2022/06/bhp-unveils-world-first-automated-shiploaders (accessed June 7, 2023).

BHP (2022b). This is IROC - BHP's Integrated Remote Operating Centre in Western Australia. https://www.youtube.com/watch?v=VPuWp3y0R-s (Accessed September 12, 2023).

Booher, H. (2003). *Handbook of human systems integration.* New York: Wiley.

Burgess-Limerick, R. (2020). Human-systems integration for the safe implementation of automation. *Mining, Metallurgy & Exploration, 37*, 1799-1806.

Burgess-Limerick, R., Joy, J., Cooke, T. & Horberry. T (2012). EDEEP - An innovative process for improving the safety of mining equipment. *Minerals*, *2*, 272-282.

Burgess-Limerick, R., Horberry, T., Cronin, J., & Steiner, L. (2017). Mining automation human-systems integration: A Case study of success at CMOC-Northparkes. *Proceedings of the 13th AusIMM Underground Operators' Conference 2017*, pp 93-98. Melbourne: AusIMM.

Burgess-Limerick, R., Krupenia, V., Wallis, G., Pratim-Bannerjee, A., & Steiner, L. (2010). Directional control-response relationships for mining equipment. *Ergonomics, 53*, 748-757.

Boloz, L. & Bialy, W. (2020). Automation and robotisation of underground mining in Poland. *Applied Sciences, 10*, 7221.

Brodny, J. & Tutak, M. (2018). Exposure to Harmful Dusts on Fully Powered Longwall Coal Mines in Poland. *International Journal of Environmental Research and Public Health, 15,* 1846.

Burger, D.J. (2006). Integration of the mining plan in a mining automation system using state-of-the-art technology and De Beers Finch mine. *The Journal of the South African Institute of Mining and Metallurgy, 106*, 553-559.

Butcher, A. (2023). The future of autonomous mining. *Solid Ground*. https://solidground.sandvik/the-future-of-autonomous-mining/ (accessed, June 8, 2023).

Chan, R. (2022). Safety-first approach drives remote dozer solution. *Australian Mining* .https://www.australianmining.com.au/safety-first-approach-drives-remote-dozer-solution/ (accessed June 15, 2023)

Chirgwin, P. (2021a). Skills development and training of future workers in mining automation control rooms. *Computers in Human Behavior Reports, 4*, 100115.

Chirgwin, P. (2021b). In Control With Higher Education Through Work-Based Learning. *Journal of Higher Education Theory and Practice*, *21(*15), 43-52.

Cholteeva, Y. (2021). Autonomous light vehicles: how driverless technology is trickling down through Australian mining. Mining Technology. https://www.mining-technology.com/features/autonomous-light-vehicles-how-driverless-technology-is-trickling-down-through-australian-mining/ (accessed June 7, 2023).

Constantine, L.L. & Lockwood, L.A.D. (2001) *Structure and Style in Use Cases for User Interface Design*. In M. van Harmelen (ed.), Object-Modeling and User Interface Design. Addison-Wesley.

Corke, P., Roberts, J. & Winstanley, G. (1998). Vision-based control for mining automation. *IEEE Robotics & Automation Magazine*. Dec, 44-49.

Corke, P., Roberts, J., Cunningham, J., & Hainsworth, D. (2008). Mining Robotics. Chapter 49 in Siciliano, B., & Khatib, O. (Eds). *Springer Handbook of Robotics*. pp., 1127-1150.

Craig, B. (2022). Western Australia Iron Ore Update. Presentation & Speech. October 3, 2022. https://www.bhp.com/-/media/documents/media/reports-and-presentations/2022/221003_waiospeeches.pdf (accessed June 3, 2023).

Cressman, T.J. (2023). Assisting operators of tomorrow. *Proceedings of the 26th World Mining Congress*. Brisbane, June 2023. pp. 283-294.

Cummings, M.L. (2023a) Revising human-systems engineering principles for embedded AI applications. *Frontiers of Neuroergonomics*. 4:1102165.

Cummings, M.L. (2023b). What self-driving cars tell us about AI risks. *IEEE Spectrum*. https://spectrum.ieee.org/self-driving-cars-2662494269 (accessed July 31, 2023).

Dragt, B.J., Camisani-Calzolari, F.R., & Craig, I.K. (2005). An overview of the automation of load-haul-dump vehicles in an underground mining environment. *Proceedings of the International Federation of Automatic Control, 16th Triennial World Congress*, Prague. pp. 37-48.

Du Venage, G. (2019). Fully automated sub level caving goes live in Mali. *Engineering and Mining Journal, 220(1)*, 38.

Dudley, J. J. (2014). *Enhancing awareness to support teleoperation of a bulldozer.* MPhil Thesis, School of Mechanical and Mining Engineering, The University of Queensland.

Dudley, J .J., Aw, J., & McAree, P. R. (2013). Minimal Perception Requirements to Support Effective Remote Control of Bulldozers (ACARP Project C20021). Brisbane Qld Australia: ACARP

Dudley, J.J. & McAree, R. (2016). Shovel Load Assist Project - ACARP Project Report C16031. Brisbane Qld Australia: ACARP (Australian Coal Industry Research Program)

Duff., E., Roberts, J., & Corke, P.I. (2002). Automation of an underground mining vehicle using reactive navigation and opportunistic localisation. *Proceedings of the 2002 Australasian Conference on Robotics and Automation*. pp. 151-156.

Dunbabin, M., & Corke, P. (2006). Autonomous Excavation Using a Rope Shovel. In: Corke, P., Sukkariah, S. (eds) *Field and Service Robotics. Springer Tracts in Advanced Robotics,* vol 25. Springer, Berlin, Heidelberg.

Dunn, M., Reid, D., & Ralston, J. (2015). Control of Automated Mining Machinery Using Aided Inertial Navigation. In J. Billingsley and P. Brett (eds.), *Machine Vision and Mechatronics in Practice*. Springer, Berlin, Heidelberg. p. 1-9.

Dunn, M.T., Reid, P.B., Thompson, J.P. & Beyers, J.G. (2023). Applications of advanced sensors and digital platforms for undergound mining automation. *Proceedings of the 26th World Mining Congress.* Brisbane, June 2023. pp. 306-320.

Dyson, N. (2020). Underground automation leader reaps benefits. *Australian Mining Monthly*. https://www.miningmonthly.com/technology-innovation/news/1378395/underground-automation-leader-reaps-benefits (accessed June 8, 2023).

Dyson, N. (2020). Syama's automation surge. *Mining Magazine*. https://www.miningmagazine.com/technology-innovation/news/1387604/syama%E2%80%99s-automation-surge (accessed, August 6, 2023).

Eastwood, A. (2023). Million-metre milestone. *Australian Mining*. https://www.australianmining.com.au/million-metre-milestone/ (Accessed September 12, 2023).

Ellis, Z. (2023). Autonomous surface drilling: KGHM Robinson mine. *Presentation to the Mine Automation and Emerging Technologies Health and Safety Partnership meeting*, September 21, 2023.

European Organisation for the Safety of Air Navigation (Eurocontrol) (2019) *Human Factors Integration in ATM System Design*. https://www.eurocontrol.int/publication/human-factors-integration-atm-system-design. (Accessed Nov 28, 2023).

Fisher, B.S. & Schnittger, S. (2012). *Autonomous and remote operation technologies in the mining industry: Benefits and costs*. BAE Research Report 12.1. Canberra: BAEconomics Pty Ltd.

Folds, D. (2015). Systems engineering perspective on human systems integration. In D. Boehm-Davis, F. Durso, & J. Lee (Eds.), *APA Handbook of Human Systems Integration*. Washington, DC: American Psychological Association.

Fouche, L. (2023). Vehicle fatality elimination. Presentation to the Collision Avoidance Forum 2023. https://www.resourcesregulator.nsw.gov.au/sites/default/files/2023-03/Leon-Fouche-Rio-Tinto-Update-CA-Forum.pdf (accessed June 3, 2023).

FutureBridge (2022). *Autonomous Haulage Systems – The Future of Mining Operations*. https://www.futurebridge.com/industry/perspectives-industrial-manufacturing/autonomous-haulage-systems-the-future-of-mining-operations/ (accessed May 24, 2023).

Gaber, T., El Jazouli, Y., Eldesouky, E., & Ali, A. (2021). Autonomous Haulage Systems in the Mining Industry: Cybersecurity, Communication and Safety Issues and Challenges. *Electronics, 10*(11), 1357.

Ghodrati, B., Hoseinie, S.H., & Garmabaki, A.H.S. (2015). Reliability considerations in automated mining systems. *International Journal of Mining, Reclamation and Environment, 29*, 404-418.

Gibson, M. (2018). Go behind the wheel of Fortescue Metals Group's driverless trucks at its Solomon mine site. *The West Australian.* 20, February, 2018.

Gleeson, D. (2021). Glencore showcases automated longwall advancements at Oaky Creek. *International Mining*. https://im-mining.com/2021/09/30/glencore-showcases-automated-longwall-advancements-oaky-creek/ (accessed June 7, 2023).

Gleeson, D. (2021). Thiess hits new heights with SATS dozer technology at Lake Vermont. *International Mining.* https://im-mining.com/2021/06/02/thiess-hits-new-heights-sats-dozer-technology-lake-vermont/ (accessed August 9, 2023).

Gleeson, D. (2022). Anglo American's longwall automation milestone recognised in awards ceremony. *International Mining.* https://im-mining.com/2022/09/02/anglo-americans-longwall-automation-milestone-recognised-in-awards-ceremony/ (accessed June 7, 2023).

Gleeson, D. (2022). Thiess, WesTrac and Cat collaborate on 'world-first' autonomous drilling feat. *International Mining*. https://im-mining.com/2022/09/06/thiess-westrac-and-cat-collaborate-on-world-first-autonomous-drilling-feat/ (accessed August 9, 2023).

Gleeson, D. (2023). Huawei boosts Shaanxi Coal production efficiency & safety with 5G-backed solution. *International Mining.* https://im-mining.com/2023/05/18/huawei-boosts-shaanxi-coal-production-efficiency-and-safety-with-5g-backed-solution/ (accessed July 17, 2023).

GMG (2019). Guideline for the implementation of autonomous systems in mining. https://gmggroup.org/wp-content/uploads/2019/06/20181008_Implementation_of_Autonomous_Systems-GMG-AM-v01-r01.pdf

GMG (2021). Rio Tinto's experience with automation improving safety for employees and creating value. https://gmggroup.org/wp-content/uploads/2021/03/2021-01-11-Rio-Tintos-Experience-with-Automation-and-People.pdf (accessed June 7, 2023).

Gordon, S.E. (1994). *Systematic Training Program Design: Maximising Effectiveness and Minimizing Liability*. Englewood Cliffs, NJ: Prentice Hall.

Hariyadi, A., Castro, M., & Fisher, J. (2016). Automated Train Ore Transport. In *Proceedings of the Seventh International Conference & Exhibition on Mass Mining (MassMin 2016)*. pp 563-570 Melbourne: AusIMM.

Hassall, M. E., Sanderson, P. P., and Cameron, I. T. (2014). The development and testing of SAfER: a resilience-based human factors method. *Journal of Cognitive Engineering and Decision Making, 8,* 162-186.

Hassall, M., Seligmann, B., Lynas, D., Haight, J & Burgess-Limerick, R. (2022). Predicting human-system interaction risks associated with autonomous systems in mining. *Human Factors in Robots, Drones and Unmanned Systems, 57*, 78–85.

Horberry, T. (2012). The Health and Safety Benefits of New Technologies in Mining: A Review and Strategy for Designing and Deploying Effective User-Centred Systems. *Minerals*, *2*, 417-425.

Horberry, T., Burgess-Limerick, R., & Steiner, L. (2011). *Human factors for the design, operation and maintenance of mining equipment*. Boca Raton: CRC Press.

Horberry, T., Burgess-Limerick, R & Steiner, L. (2018). *Human-Centered Design for Mining Equipment and New Technology*. Boca Raton: CRC Press.

ICMM (2015). *Critical Control Management: Implementation Guide.* London: International Council of Mining and Metals.

International Council on Systems Engineering (2015). *INCOSE Systems Engineering Handbook : A Guide for System Life Cycle Processes and Activities*. Wiley.

International Council on Systems Engineering (2023). *Human Systems Integration: A Primer. Volume 1*. INCOSE.

International Energy Agency (2022) *The Role of Critical Minerals in Clean Energy Transitions.* World Energy Outlook Special Report. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions (accessed July 30, 2023).

International Standards Organisation (2010). *Safety of machinery — General principles for design — Risk assessment and risk reduction*. ISO 12100: 2010.

International Standards Organisation (2010). *Ergonomics of human-system interaction Part 210: Human-centred design for interactive systems*. ISO9241-210. p. 9.

International Standards Organisation (2012). *Safety of machinery — Risk assessment — Part 2: Practical guidance and examples of methods*. ISO/TR14121-2: 2012.

Ishimoto, H. & Hamada, T. (2020). Safety Concept and Architecture for Autonomous Haulage System in Mining. *Proceedings of the 37th International Symposium on Automation and Robotics in Construction*. pp. 377-384.

Knights, P., & Yeates, G. (2021). Progress toward zero entry mining: Automation enabling safer, more efficient mining. *IEEE Industrial Electronics Magazine*, *15*, 32-38.

LaTourrette, T. & Regan, L. (2022). *Barriers to the commercialization and adoption of new underground coal mining technologies in the U.S*. Interim results. RAND Corporation. https://www.rand.org/pubs/working_papers/WRA1575-1.html (accessed August 8, 2023).

Leonida, C. (2023). Dig, Load, Haul — Repeat. *Engineering & Mining Journal.* https://www.e-mj.com/features/dig-load-haul-repeat/ (accessed June 8, 2023).

Lööw, J., Johansson, B., Andersson, E., & Johansson, J. (2018). *Designing Ergonomic, Safe, and Attractive Mining Workplaces*. CRC Press.

Li, J-g & Shan, K. (2018). Intelligent Mining Technology for an Underground Metal Mine Based on Unmanned Equipment, *Engineering, 4*, 381-391.

Lever, P. (2011). Automation and robotics. *SME Mining Engineering Handbook*. (3rd Ed.). Society for Mining, Metallurgy and Exploration. pp. 805-824.

Leeming, J.J. (2023). Full automation of resin Roofbolting in soft rock mining. Proceedings of the 26th World Mining Congress. Brisbane, June 2023. pp. 405-414.

Leveson, N.G. (2012). *Engineering a safer world: systems thinking applied to safety*. MIT Press.

Leveson, N.G. & Thomas, J.P. (2018). *STPA handbook*. MIT.

Luxberger, K. (2023). Eliminating barriers for the implementation of automation in the mining industry. Presentation to the Mine Automation and Emerging Technologies Health and Safety Partnership, September 21, 2023.

Lynas, D. & Burgess-Limerick, R. (2019). Whole-body vibration associated with dozer operation at an Australian surface coal mine. *Annals of Work Exposures and Health*, *63*, 881–889.

Lynas, D. & Horberry, T. (2011). Human factor issues with automated mining equipment. *The Ergonomics Open Journal, 4(Suppl 2-M3),* 74-80.

Lynas, D., Horberry, T., Burgess-Limerick, R., Haight, J. & Hill, A. (2023). *Automation in mining database of installations*. ACARP C34026 progress report.

Marshall, J.A., Bronchi's, A., Reboot, E., & Scheming, S. (2016). Robotics in mining. Chapter 59 in Siciliano, B., & Khatib, O. (Eds). *Springer Handbook of Robotics*. (2nd Ed.). pp. 1549-1576.

Martin, T. & Clough, A. (2021). Queensland Coal Mining Board of Inquiry Report: Part 2. https://www.coalminesinquiry.qld.gov.au/ (accessed June 9, 2021).

McAree. R., Hensel, R. and Smith, Z. (2017). *Automated Bulk Dozer Push - Reducing the Cost of Overburden Removal*. (ACARP C24037) Brisbane Qld Australia: ACARP.

Meers, L. Van Duin, S., & Ryan, M. (2013). Rapid roadway development. *Proceedings of the 30th International Symposium on Automation and Robotics in Construction and Mining*; Held in conjunction with the 23rd World Mining Congress, Montreal.

Melnik, G., Roth, E., Multer, J., Safar, H., & Isaacs, M. (2018). *An Acquisition Approach to Adopting human Systems Integration in the Railroad Industry*. US DOT. DOT/FRA/ORD-18/05.

Moore, P. (2021). Anglo American inaugurates its first global Integrated Remote Operations Centre in Santiago for running Los Bronces. *International Mining*. https://im-mining.com/2021/04/06/anglo-american-inaugurates-first-global-integrated-remote-operations-centre-santiago-running-los-bronces/ (accessed September 8, 2023).

Moore, P. (2022). Digital transformation leaps forward with new IROC for Centinela. *International Mining*. https://im-mining.com/2022/04/28/digital-transformation-leaps-forward-with-new-iroc-for-centinela/ (accessed September 12, 2023).

Moore, P. (2023a). Komatsu starts commercial teleop of large ICT mining dozers at Anglo's Minas-Rio. *International Mining*. https://im-mining.com/2023/06/14/komatsu-starts-commercial-teleop-of-large-ict-mining-dozers-at-anglos-minas-rio/ (accessed June 15, 2023).

Moore, P. (2023b). Anglo American Los Bronces – inside the IROC. *International Mining*. https://im-mining.com/2023/08/22/anglo-american-los-bronces-inside-the-iroc/ (accessed August 23, 2023).

Moreau, K., Lamanen, C., Bose, R., Shang, H., & Scott, J.A. (2021). Environmental impact improvements due to introducing automation into underground copper mines. *International Journal of Mining Science and Technology, 31*, 1159-1167.

Morton, J. (2017). New blast hole drill rigs feature more autonomy. *Engineering and Mining Journal*, March, 28-35.

Nebot, E. (2007). Surface Mining: Main research issues for autonomous operation. *Robotics Research, Springer Transactions in Advanced Robotics, 28*, 268-280.

NSW Resources Regulator (2019). Collision between semi-autonomous dozer and an excavator. DOC19/758086.

Ninness, J. (2018). Autonomous mining trucks | Are there any limitations? Australasian Mine Safety Journal, November 13. https://www.amsj.com.au/autonomous-mining-truck-safety/ (accessed May 24, 2023).

Onifade M., Said, K.O., & Shivute, A.P. (2023). Safe mining operations through technological advancement. *Process Safety and Environmental Protection, 175*, 251-258

Paraszczak, J., Gustafson, A. & Schunnesson, H. (2015) Technical and operational aspects of autonomous LHD application in metal mines, *International Journal of Mining, Reclamation and Environment*, *29*, 391-403.

Paredes, D., & Fleming-Munoz, D. (2021). Automation and robotics in mining: Jobs, income and inequality implications. *The Extractive Industries and Society, 8*, 189-193

Pascoe, T. (2020). *An Evaluation of Driverless Haul Truck Incidents on a Mine Site: A Mixed Methodology.* Unpublished PhD thesis. Curtin University of Technology.

Pascoe, T., McGough, S., & Jansz, J. (2022a). A Multi-Industry Analysis of Human-Machine Systems: The Connection to Truck Automation. *World Safety Journal, XXXI*(1), 1-38.

Pascoe, T., McGough, S., & Jansz, J. (2022b). From truck driver awareness to obstacle detection: A tiger never changes its stripes. *World Safety Journal, XXXI*(2), 15–28.

Pascoe, T., McGough, S., & Jansz, J. (2022c). Haul Truck Automation: Beyond Reductionism to Avoid Seeing Turtles as Rifles. *World Safety Journal, XXXI*(3), 26–38.

Pascoe, T., McGough, S., & Jansz, J. (2022d). The experiences of mineworkers interacting with driverless trucks: risks, trust and teamwork. *World Safety Journal, XXXI*(4), 19-40.

Peng, S.S., Du, F., Cheng, J., & Li, Y. (2019). Automation in U.S. longwall coal mining: A state-of-the-art review. *International Journal of Mining Science and Technology, 29*, 151-159.

Perry, A. (2022). BHP is accelerating automation for safer operations. Mining Safe to Work. October 6. https://safetowork.com.au/bhp-is-accelerating-automation-for-safer-operations/ (accessed May 24, 2023).

Price, R., Cornelius, M., Burnside, L. & Miller, B. (2019). Mine Planning and Selection of Autonomous Trucks. In Topal, E. (eds) *Proceedings of the 28th International Symposium on Mine Planning and Equipment Selection*. Springer.

PWC (2023). Mine 2023: 20th Edition. The era of reinvention. https://www.pwc.com/gx/en/industries/energy-utilities-resources/publications/mine.html (accessed June 12, 2023).

Quinteiro, C., Quinteiro, M., & Hedstrom, O. (2001). Underground iron ore mining at LKAB, Sweden. Underground mining methods: engineering fundamentals and international case studies, 361-368.

Ralston, J.C., Hargrave, C.O., & Dunn, M.T. (2017). Longwall automation: trends, challenges and opportunities. *International Journal of Mining Science and Technology, 27*, 733-739.

Ralston, J.C., Hargrave, C.O., Dunn, M.T. & Burgess-Limerick, R. (2017). Assistive shuttle car system: Stage 1 architecture. ACARP project C26049 final report.

Ralston, J.C., Hargrave, C.O. & Hainsworth, D.W. (2006). Development of an Autonomous Conveyor-Bolting Machine for the Underground Coal Mining Industry. In: Yuta, S., Asama, H., Prassler, E., Tsubouchi, T., Thrun, S. (eds) *Field and Service Robotics*. Springer Tracts in Advanced Robotics, vol 24. Springer, Berlin, Heidelberg.

Ralston, J., Reid, D., Hargrave, C., & Hainsworth, D. (2014). Sensing for advancing mining automation capability: A review of underground automation technology development. *International Journal of Mining Science and Technology, 24*, 305-310.

Ralston, J.C., Reid, D.C., Dunn, M.T. & Hainsworth, D.W. (2015). Longwall automation: Delivering enabling technology to achieve safer and more productive underground mining. *International Journal of Mining Science and Technology, 25*, 865-876.

Redwood, N. (2023). Autonomous Swarm Haulage: The Economics of Autonomous Haulage with Small Trucks. https://20485703.fs1.hubspotusercontent-na1.net/hubfs/20485703/Pronto-Whittle%20Swarm%20Haulage%20Study.pdf (accessed Aug 4, 2023).

Reid, D.C., Ralston, J. C., Dunn, M. T. & Hargrave, C. O. (2011). A Major Step Forward in Continuous Miner Automation, *11th Underground Coal Operators' Conference*, 165-171.

Reinach, S. & Jones, M. (2007). *An Introduction to Human Systems Integration (HSI) in the U.S. Railroad Industry*. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Rio Tinto (2019). How did one of the world's largest robots end up here? https://www.riotinto.com/en/news/stories/how-did-worlds-biggest-robot (accessed June 7, 2023).

Roberts, J.M., Duff, E.S., Corke, P.I., Sikka, O., Winstanley, G.J., & Cunningham, J. (2000). Autonomous control of underground mining vehicles using reactive navigation. *Proceedings of the 2000 IEEE International Conference on Robotics & Automation*, April, San Francisco, CA. pp. 3790-3795.

Salas, E., & Cannon-Bowers, J. (2001). The science of training: A decade of progress. *Annual Reviews of Psychology, 52,* 471–499.

Scheding, S., Dissanayake, G., Nebot, E. M. & Durrant-Whyte, H. (1999) An experiment in autonomous navigation of an underground mining vehicle. *IEEE Transactions on Robotics and Automation, 15*, pp. 85-95.

Schiffbauer, W.H. (1997). *Accurate Navigation and Control of Continuous Mining Machines for Coal Mining*. Report of Investigations 9642. NIOSH.

Schiffbauer, W.H., Yenchek M.R., & Lutz, T. (2007). *Remote vision system for dozers on coal stockpiles*. IEEE Industry Applications Annual Meeting, p. 2096-2101.

Schmidt, R.A., & Bjork, R.A. (1992). New conceptualizations of practice: Common principles in three paradigms suggest new concepts for training. *Psychological Science, 3*, 207–217.

Swart, C. & Miller, F., Corbeil, P.A., Falmagne, V. & St-Arnaud, Luc. (2002). Vehicle automation in production environments. *Journal of the South African Institute of Mining and Metallurgy, 102*. 139-144.

Standards Australia. AS 7470 (2016). *Human Factors Integration in Engineering Design - General Requirements.* https://www.rissb.com.au/products/as-7470-human-factors-integration-in-engineering-design-general-requirements/ (accessed Nov 28, 2023).

Stentz, A., Bares, J., Singh, S., & Rowe, P. (1999). A Robotic Excavator for Autonomous Truck Loading. *Autonomous Robots 7*, 175–186.

Tampier, C. Mascaro, M., & Ruiz-del-Solar, J. (2021). Autonomous Loading System for Load-Haul-Dump (LHD) Machines Used in Underground Mining. *Applied Sciences*. 2021; 11(18):8718.

Tariq, M., Gustafson, A., & Schunnesson, H. (2023) Training of load haul dump (LHD) machine operators: a case study at LKAB's Kiirunavaara mine, *Mining Technology*, DOI: 10.1080/25726668.2023.2217669

Taylor, B. & Spångberg, C. (2023). Shifting the needle on safety at the face - wireless development charging with Orica and Epiroc's Avatel™ charging solution. *Proceedings of the 26th World Mining Congress*. Brisbane, June 2023. pp 1856-1865.

Theiss (2021). Thiess applies SATS technology at Lake Vermont. https://thiess.com/news/innovation/thiess-applies-sats-technology-at-lake-vermont (accessed June 7, 2023).

Thompson, B. (2014). Safety trends in mining. Proceedings of the 6th International Platinum Conference. The Southern African Institute of Mining and Metallurgy.

Thompson, R.J. (2011). Mine Road Design and Management In Autonomous Hauling Operations: A Research Roadmap. *Proceedings of the Second International Future Mining Conference*. Paper 21.

UK Defence Standardization (2015) Def Stan 00-251. Human Factors Integration for Defence Systems. https://standards.globalspec.com/std/9991051/def-stan-00-251-part-1

UK Ministry of Defence (2021). Joint Service Publication 912. Human Factors Integration for Defence Systems. https://assets.publishing.service.gov.uk/media/623360c8e90e0779a2c994e7/JSP912_Part_1.pdf

USA Air Force (2009). *Air Force Human Systems Integration Handbook.* https://www.acqnotes.com/Attachments/Air%20Force%20Human%20System%20Integration%20Handbook.pdf

USA Department of Defense (2008). *Instruction 5000.02. Operation of the Defense Acquisition System.* https://www.acqnotes.com/Attachments/DoD%20Instruction%205000.2.pdf

USA Department of Defense (2020). *Instruction 5000.88 Engineering Defense Systems.* https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/500088p.PDF

USA Department of Defence (2022a). *Directive 5000.01 The Defense Acquisition System.* https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodd/500001p.pdf

USA Department of Defense (2022b). *Instruction 5000.95. Human Systems Integration in Defense Acquisition*. https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/500095p.PDF

USA Department of Defence (2022c). *Human Systems Integration Guidebook*. Office of the Under Secretary of Defense for Research and Engineering. https://www.cto.mil/wp-content/uploads/2023/06/HSI-Guidebook-2022.pdf

USA Federal Aviation Administration (1993). Order 9550.8. *Human Factors Policy*. https://www.faa.gov/documentLibrary/media/Order/9550.8.pdf

USA Federal Aviation Administration (2016). HF-STD-004a. *Human Factors Engineering Requirements*. https://hf.tc.faa.gov/publications/2016-09-human-factors-engineering-requirements/HF-STD-004A.pdf

USA National Aeronautics and Space Agency (2015). *Space flight human-system standard. Volume 2: Human factors, habitability, and environmental health.* NASA-STD-3001, Volume 2, revision A. http://https://standards.nasa.gov/standard/NASA/NASA-STD-3001-VOL-2

USA National Aeronautics and Space Agency (2021). *Human Systems Integration Handbook.* http://https://ntrs.nasa.gov/citations/20210010952

Van Duin, S., Meers, L., Donnelly, P & Oxley, I. (2103). Automated bolting and meshing on a continuous miner for roadway development. *International Journal of Mining Science and Technology, 23*, 55-61.

Valivaara, J. (2016). Automated Drilling Features for Improving Productivity and Reducing Costs in Underground Development. *Proceedings of the Seventh International Conference and Exhibition on Mass Mining (MassMin 2016)*, pp 723-730 AusIMM: Melbourne.

Vega, H. & Castro, R. (2020). Semi Autonomous LHD operational philosophy for panel caving applications. In R Castro, F Báez & K Suzuki (eds), MassMin 2020: Proceedings of the Eighth International Conference & Exhibition on Mass Mining, University of Chile, Santiago, pp. 1313-1321.

Wang, J. & Huang, Z. (2017). The recent technological development of intelligent mining in China. *Engineering, 3*, 439-444.

Westrac (2022). Collaboration delivers world first autonomous drilling success for Thiess. https://www.westrac.com.au/blog/collaboration-delivers-world-first-autonomous-drilling-success-for-thiess (accessed September 12, 2023).

Wiener, E.L. (1989). Human factors of advanced technology (“glass cockpit”) transport aircraft. NASA Contractor Report 177528, NASA Ames Research Center.

Xiao, W., Liu, M., Chen, X. (2022). Research Status and Development Trend of Underground Intelligent Load-Haul-Dump Vehicle—A Comprehensive Review. *Applied Sciences, 12*, 9290.

Westrac (2023). *The evolution of automation in mining*. White paper 32023.

Winstanley, G., Usher, K., Corke, P., Dunbabin, M. & Roberts, J. (2007). Dragline automation—A decade of development. *IEE Robotics and Automation Magazine*, September. 52-64.

Xie, J., Yang, Z., Wang, X., & Wang, Y. (2018). A remote VR operation system for a fully mechanised coal-mining face using real-time data and collaborative network technology. *Mining Technology, 127*, 230-240.

Yaghini, A., Hall, R., Apel, D. (2022). Autonomous and Operator-Assisted Electric Rope Shovel Performance Study. *Mining, 2*, 699–711.