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From truck driver awareness to obstacle detection: A tiger never changes its stripes

Todd Pascoe*, Shirley McGough, and Janis Jansz
Curtin University, Western Australia

KEYWORDS

Artificial intelligence
Haul truck automation
Machine learning
Driverless technology

ABSTRACT

To inform the design of artificial intelligent systems on a mine site, incidents involving driverless haul trucks were evaluated to understand the risk implications of automation in its application. Safety-related incidents (n = 998) on a mine site in Western Australia (WA) were recorded to analyse events involving driverless and manually operated haul trucks since the operation began back in 2013. Truck incidents were evaluated and compared on their characteristics and investigation findings. From FY14 through to FY18, the incident frequency of manually driven haul trucks averaged 968 incidents per 1,000,000 hours driven, while the driverless trucks averaged 866. Driver awareness was the most frequent hazard associated with manually operated haul trucks, while haul road conditions (objects identified or not) were the most common hazard associated with automated haul trucks.

Data analysis demonstrates how driverless trucks transformed a mine site's risk profile, rather than underpin the popular notion that automation eliminates the risks associated with surface mobile equipment. Therefore, risk management should focus on enhancing users' knowledge of computer programming and machine learning techniques that is driving the most progress in industry to-date. Such a focus would legitimise the current progress of artificial intelligence and highlight the residual workload of humans whose roles are transforming and adapting to the introduction of driverless technology.

1. INTRODUCTION

Haul trucks are a vital component of a mining supply chain. They also hold the potential cause fatal incidents from unintended situations. According to the Department of Mines, Industry Regulation and Safety (2014), there were five fatal haul truck incidents in Western Australia between 2000 and 2012. Although the elimination of haul truck incidents is yet to be achieved, driverless technology is being introduced to remove human exposure to truck driving hazards. Automated systems have also been proven to be effective in reducing significant incidents (Udd, 2019). This is largely due to the fact that permission-based control systems coordinates truck movements by permitting exclusive sections to the road (Hamada & Saito, 2018).

Corresponding author: toddpascoe@hotmail.com

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Furthermore, manual equipment are provided with a system-based interface to manage haul truck interactions. Digital interfaces highlight the location of surrounding vehicles and sections of road occupied by the driverless vehicles. Despite the direct benefits of automation, new hazards and risks have emerged. These hazards and risks are unique to a driverless operation have played a role in the unconventional incident types involving driverless haul trucks (Department of Mines and Petroluem, 2015b).

The WA mining industry's risk transformation is being driven by the rapid introduction of artificial intelligence (Gray, 2019). According to recent reports, there are now more than 350 automated haul trucks in the Pilbara region (BHP, 2019; Fortescue Metals Group Limited, 2019; Jacques, 2019). There are also plans to expand BHP's driverless strategy across its entire iron ore and coal open cut operations (Palmer, 2019). Introducing automated systems, however, has already highlighted a number of important lessons (Department of Mines and Petroluem, 2014); particularly those that have already been learnt in Aviation, Maritime and Manufacturing (Dekker & Woods, 2002; Lee & Morgan, 1994; Woods, 2016). Yet, the same signs and symbols of human–machine breakdown appear to be repeating themselves—just simply in another industry context. Over the last six years, driverless haul trucks have been involved in a number of significant incidents ("BHP blames heavy rains for autonomous trucks crash," March, 2019; Department of Mines and Petroluem, 2015b; "Fortescue Metals Group auto haul truck crash Christmas Creek 'no failure' of system," February, 2019). These new types of incidents have sparked interest in the safety aspects of self-driving vehicles. More importantly, how automated systems are adapting and changing to the complex situations that arise on mine sites.

In order for driverless technology to succeed, there is an urgent need to assist the WA Mining Industry with empirical research on the risk profile changes. The WA Department of Mines, Industry Regulation and Safety published a Code of Practice surrounding the safe use of autonomous mobile equipment (Department of Mines and Petroluem, 2015a). However, like any new technology, there are limited empirical studies on the implications of its practical application. This can also be said for research publications, where driverless technology is yet to be critically evaluated in a complex mining environment. Therefore, there was a real need for this safety research. Not only to support the mining industry on their journey, but to assist academia in keeping abreast with the industry's technological innovation.

Driverless technology has so far been viewed as the solution to safety. A computerised system that can do no wrong (ADVI Hub, 2016, June 27). The assumption is that the substituting of human cognition can eliminate the risks of truck driving. Without a human, there can be no possible lapses in concentration or fatigue related events behind the wheel. A truck is expected to navigate corners and bends, while also reversing towards excavators, dump faces and drop cuts. Removing the driver effectively eliminates human exposure to high-risk tasks. Secondly, by substituting the operator, people are no longer exposed to 'hazardous' driving behaviours. The assumption is that once control is transferred to a computer, people who remain are no longer exposed to a 400-tonne haul truck. Since trucks are now given assignments, execute those instructions and performing nothing else. On that basis, the value proposition stakes up, given that these assumptions reign true. However, if automation were to eliminate the risk entirely, then there would not have been any significant incidents?

Although there are no longer people behind the wheel, the uncontrolled nature of a driverless truck incident highlights the possibilities. There are also light vehicles, dozers, loaders and excavators still operated manually on the mine. Even if driverless trucks were only involved, investigators would be hard pressed to argue how a person could not be exposed. Evaluation of risk is this new era is a real balance between foreseeability and tolerability. A bandwidth between treating every incident as severe, versus the perception that there is no risk at all. The point here, is that if systems and processes

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breakdown when humans are not involved, who is to say it would not happen when they were? This study is not a criticism of driverless technology, more the opposite. If the technology is not deeply understood, there is a real possibility that the industry could discard driverless vehicles entirely. Left flat footed on the back of the hype cycle as it stumbles through the trough of disillusionment (Panetta, 2019, August 29). There is reason why this paper is titled: "From driver awareness to obstacle detection: a tiger never changes it's stripes". The introduction of driverless technology has not eliminated safety risk, it has removed human exposure and exploited what was left. The trucks are still big, yellow and mobile: they are just now being controlled by a computer.

2. METHODOLOGY

2.1 Data Collection

The method involved collecting health and safety incidents involving manual and automated trucks. The incident data was extracted from a safety database, setting a date range from Financial Year 2014 (FY14) to 2018 (FY18). This four-year period is a reflection of WA mine sites' transition from manual to fully automated control. The transition period enabled the research to follow the full deployment of driverless haul trucks and the reverberations on safety.

Collecting raw incident data required setting specific parameters in the database. Firstly, each Department's data was selected to obtain the entire range of haul truck-related incidents. Department incident data was filtered for health, safety, environment and financial impacts. This method was adopted to ensure every incident reported could be found. Moreover, incidents that may have been incorrectly assigned impact types could be identified (i.e. environment over safety). There were also noteworthy observations made during data collection. The researcher was made aware of certain haul truck-related incidents; yet, they were unable to be locatable in database. Search functions had only been set for health and safety. It was soon found that a significant portion of driverless incidents were allocated 'financial' impacts over 'safety'. Once financial impacts were added, a number of additional haul truck incidents emerged. This observation was an interesting finding leading into the research. The discovery left the researcher asking, 'how were driverless haul trucks incidents being assessed?'

The exported information was tabled into an excel spreadsheet. Incident data was automatically tabled into various columns for every event. Columns included the incidents' unique identifier, date, department, title, investigation, severity and who it was reported by. Incident findings were obtained from the long description of the report. For example, "At approximately 10:30am DT xxxx [Dump Truck] was travelling loaded towards Pxx Rom waste dump from Ex xxxx [Excavator]. DT xxxx has encountered muddy conditions causing it to briefly lose traction and breach lane". Investigation findings were included in the original notification; certain causes were outlined in a separate report. As investigation 'root cause' types were not overly insightful, the researcher analysed and coded 1,223 incidents to identify whether a truck was involved. This interpretative process provided the platform for the data analysis.

2.2 Data Analysis

The raw nature of the data required each incident to be coded. Since there were no incident types, limited root cause category and hazards assigned, more context needed to be drawn. Therefore, data coding was undertaken to ask more investigative questions of the data set:

- Did the incident involve a truck?
- Was the truck in manual or automatic control?
- What was the incident type?

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- What was the associated hazard?
- Was the hazard new, conventional or has it transformed?

These questions not only provided more context, it enhanced the quantitative aspects of the data. For example, the analysis could determine the frequency of incident types and hazards. Calculating a frequency substantiated the impact of each occurrence and its condition. In addition, the method of coding gave rise to more structure in the data. Structure increased the researcher's understanding of the phenomenon by highlighting key themes. These themes provided a clear link between incidents and their associated hazards. For example, road conditions and network communication losses were the major contributors to truck lane breaches. Drawing the link between new, conventional and transformed hazards, which highlight the reverberations of the technology.

Driving hours were also collected in an attempt to compare manual and driverless operations. For instance, even though the manual trucks had a higher number of incidents, the number of driving hours were higher. The total number of incidents were not comparable when considering the size of each operation. Moreover, self-driving car companies are using a similar metrics to measure performance. Waymo, for example, are utilising the number of kilometres travelled to measure performance. Travel time comparisons are useful; however, caution is expressed when using it as an absolute figure to measure driverless 'safety' reliability. Driverless vehicles and their equipment failure modes are a very small component in an open, dynamic and complex environment. Therefore, the frequency of incidents should be used as indicator, not a baseline for failure modes. Nonetheless, the results provide an interesting perspective on the consequences of introducing driverless technology on a mine site.

3. RESULTS

3.1 The frequency of haul truck incidents reduced across site

The mine site's truck incident frequency significantly reduced over the four years (Figure 1). The graph highlights a 91% reduction from Financial Year 2014 to 2018. A total of 998 trucks incidents were identified in the database. The data represents incidents that occurred during the transition from manual to driverless control. Reducing the site's incident frequency was underpinned by an uplift in truck hours and a reduction in the number of incidents.

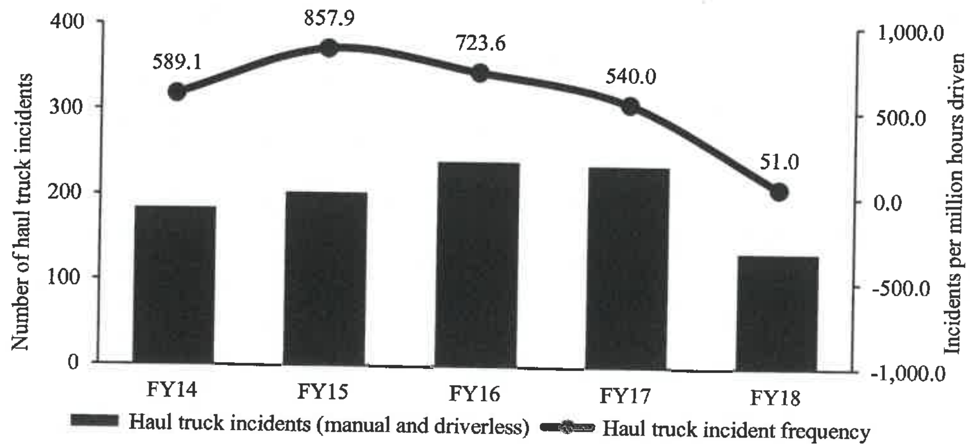

Figure 1: Site haul truck incident frequency[a]

[a] *Frequency was calculated based on the number of incidents in both the manual and driverless operation, divided by the number of hours driven, times a million.*

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The mine site's incident frequency averaged 921.4 incidents per million hours driven. Over a million truck hours were driven by both operations. The highest incident frequency was recorded in the manual operation. Manual trucks recorded 968 incidents per million hours driven. Despite manual driving hours exceeding the driverless operation, the hours did not offset the high number of incidents. Comparingly, the driverless operation registered 866 incidents per million hours driven. Although there was a year-on-year increase in the number of 'unconventional' incidents, the uplift was not substantial enough to impact the frequency. Moreover, as the driverless operation expanded, the number of hours increased exponentially. Therefore, as manual operations transferred more control, the positive impact of the driverless fleet reduced the site's haul truck incident frequency. A significant portion of incidents were reduced by removing human exposures to driving hazards. For example, trucks being heavy loading, drivers seated for long period and travelling over rough roads. Injuries to the backs, shoulder and neck were the largest contributor to truck incidents. The second most frequent incident was tray damage. The repetitive nature of loading trucks left excavators operators vulnerable to misjudging tray heights. In addition, the dust generated from the excavator had reduced operator visibility of the tray.

Procedural breaches in manual were predominately traffic management breakdowns. Positive communication breakdowns occurred when drivers had not gained permission before passing. Moreover, correct radio protocols were not utilised prior to overtaking. Priority rules were in place to give more important equipment right of way. For instance, watercarts had to give way to haul trucks. The most common breaches were truck on truck. Drivers were either unsure who took priority, had not observed oncoming traffic or forgot to give way. Secondly, working graders were the highest priority when considered working. Truck drivers had to determine whether the grader's blade was grounded. Trucks did not given way when the blade was observed to be lifted or working graders were heading in the opposite direction. Another example were truck U-turns on haul roads. U-turns were performed unassisted when the driver was lost or assigned to a new load source. Drivers were unsure of the process to block the road to prevent smaller equipment from travelling into the truck's path.

Mobile equipment were to maintain 50 metres from one another. Close interactions occurred frequently in the loading area and on intersections. While heavily focused on the task, clean-up machines lost track of their proximity to other machines. For example, while watching the blade, a grader operator reversed out in front of a haul truck. In addition, trucks drove into Active Mining Areas (AMAs) while they were not permitted. Light vehicles (LV) had closed the area to conduct workplace inspections, operator change outs or equipment breakdowns. Drivers entered the area if they did not hear the radio call or identify an LV in the area. Manual trucks were frequently made contact with haul road delineation. Trucks had either misjudged the corner or did not identify the divider. The intent of dividers are to prevent haul class equipment from cutting corners and contacting smaller equipment ("HWE Mining to face retrial over death of Adam Sargeant at Yandi mine," 2014).

Loaded haul trucks tip at the crusher or waste dump. Crusher light systems notify a driver when the bin is below threshold. A number of incidents occurred when drivers tipped on a red light. Red light tipping occurred when drivers were distracted by two-way communication, assumed the light was green or forgot about the light altogether. While trucks were tipping at the crusher, trucks had also made contact with the structure. Truck drivers either misjudged the bay width, distracted by radio communications or were visually obstructed by dust. On a waste dump, there were instances of manual trucks pushing through windrows. Windrow breaches occurred when windrows were inadequate in height or built out of incompetent material.

Operators are required to isolate trucks before entering the footprint. Truck drivers were required to enter the footprint to refuel or visually inspect the machine. Drivers entered the footprint while the machine was energised during refuelling and shift change. Isolation breaches occurred when drivers

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attended to oil leaks, material hang up or possible mechanical issues. During driver interchange, trucks had made contact with the boarding ramps. When attempting to park beside the ramp, drivers misjudged the distance from the truck and to the boarding ramp.

Table 1. Manual haul truck incidents

Incident Type	Description	Total (#)	(%)
Driver injury	Harm was sustained in association with a truck (i.e. hurt while on/in a truck)	136	24.0
Truck contact	Truck was impacted by another machine (i.e. excavator)	135	23.9
Procedural breach	Tuck did not follow the procedure (i.e. entering controlled mining area)	102	18.0
Priority rules breach	Truck did not give way to another truck who had way of right	74	13.1
Delineation contact	Truck made contact with a road divider	54	9.5
Crusher contact	Truck came in contact with a crusher while attempting to tip	24	4.2
Truck slide	Truck slid on the haul road (i.e. wet road or low-grade road base)	20	3.5
Windrow breach	Truck pierced through the separation windrow on the dump	5	0.9
Boarding ramp damage	Truck contacted the ramp while swapping out the operator out of cab	5	0.9
Fuel hose damage	The hose used to fuel the truck was damaged	3	0.5
Truck alarm	An alarm was sounded due to a maintenance issue	3	0.5
Boom gate damage	The gate to prevent entry into mining area was damaged by a truck	1	0.2
Exposed edge	A truck was exposed to an open tip head in the pit	1	0.2
Fume inhalation	Truck driver inhaled diesel fumes from the machine	1	0.2
Rock spillage	Rocks were spilled on the road from a loaded haul truck	1	0.2
Uncontrolled movement	Truck had rolled or moved unintentionally without control	1	0.2
Total		566	100.0

3.2 Despite direct safety benefits, unconventional incident types emerged

Naturally, as a mining operation expands, the number of workplace incidents will increase. However, a year-on-year increase in the number of unconventional event types is vastly different. Particularly when those incidents have never been encountered before. Truck slides occurred in manual operations; however, 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. Similarly, in the early stages, when a 20 km/h zone was reached, a truck would immediately reduce its speed from 60 km/h. In addition, when roads were wet, the situation is compounded. 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.

Processes breaches were quite similar to procedural breaches. Yet, the processes were residual human tasks based on design limitations. Automation did not eliminate trucks from tipping on red lights. Mine Control were still required to remotely tip failed truck assignments. Therefore, controllers needed to observe the lighting system before overriding the truck. Remotely tipping reinforced the difference between available and observable information. Although automation successfully prevented trucks

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from entering closed AMA's, the system relied heavily on LV's to virtually lock the area. Driverless trucks drove into AMA's where light vehicles forgot to lock or engage the button effectively. Vehicles and equipment also overtook stationary trucks before taking control of them. Driverless trucks can move at any time and have limited detection capability from the side. Despite this, proximity detection enabled driverless trucks to determine the location of other vehicles. In addition, predicted travel capability detects vehicles headed for truck routes much earlier than before. Therefore, driverless trucks could be more adaptive, reducing their speed prior to the interaction. This capability had only been introduced into the WA Mining Industry post the watercart collision (Department of Mines and Petroleum, 2015b).

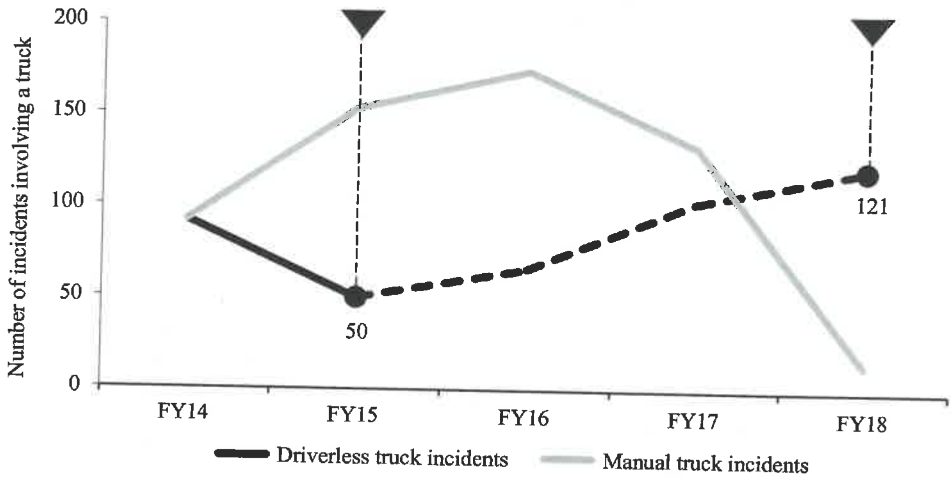

Figure 2. Increase in driverless truck incidents as manual incidents decline

Permission-based control simplified priority rules and was far more passive. As a result, priority rules breaches between haul trucks were reduced to zero. However, despite engineering controls, interactions remained administrative for manual equipment. 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 of them'. Equipment icons had also flipped to cause reactions to driverless trucks. This was evident when clean-up machines were continuously moving. Truck damage remained present within the operation. A previously stated, removing the truck driver reduced the consequence, however truck trays were still damaged. Conventional tyre separation and equipment breakdowns existed. It had simply transformed the way the trucks responded to the situation. Similar to material in loading and dumping areas. However, if the material was not surveyed into the mine model, the risk was that trucks could collide with the stockpile. In addition, full dump locations meant that trucks would attempt to reverse over the material already tipped; resulting in truck damage. Vehicles under escort were also unable to identified by the trucks. A broken escort left non-site aware vehicles with fewer layers of protection, even though trucks recognised their vehicle as an object to prevent colliding.

Personal injuries had been sustained during truck refuelling, truck testing and fault findings. Since drivers were tasked to refuel their own truck, injuries during manual refuelling were captured. A shoulder injury in driverless was sustained when lifting the hose into place. During truck testing, a production technician was injured when the retarder was engaged instantly. And after having difficulties mode changing a truck, a technician put their hand into a rotating LiDAR when it appeared to be stationary. Recovering trucks signified the retrieval of trucks from bogging after travelling

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through wet roads. Moreover, if the lane had not been surveyed then the area was permissible. Trucks had reversed over windrows that had not been surveyed into the virtual model. The truck detects the windrow initially, however once overridden; the truck attempted to achieve the dump location. However, to system technicians, it can appear to be no object in the path at all. This was observed in the survey mismatches. Trucks were found to be using dump plans based on the wrong survey data, which did not reflect the physical mine. Automation had prevented trucks from contacting the crusher with pre-defined lanes. Crushing facilities were not dynamic areas like waste dumps and loading areas. However, this did not prevent rocks from damaging the crusher when tipping out of the tray.

Table 2. Driverless truck incidents

Incident Type	Description	(#)	(%)
Lane breach	Truck had drifted outside of the assigned pathway	190	44.0
Proximity detection	Detection of potential pathway collision with machine	135	31.3
Truck damage	Truck has contacted or been contact by another machine	32	7.4
Process breach	System-based task did not comply with the procedure	31	7.2
Object detection	Identified object and stopped suddenly	14	3.2
Reversed into material	Truck reversed into a dump pile	7	1.6
Broken escort	Non-site aware vehicle became separated from escorts	4	0.9
Technician injury	Person was injured while attending to a truck	3	0.7
Production loss	Truck fleet down for extended period of time	3	0.7
Bogged truck	Caught in wet ground material	2	0.5
Uncontrolled movement	Rolling backwards or forwards uncontrollably	2	0.2
Windrow breach	Truck protruded through windrow on dump	2	0.2
Truck collision	Truck was had contact another truck	1	0.2
Ore tipped on waste	Ore material was tipped onto a waste dump	1	0.2
Rock breach bund	Rock tipped over a waste dump and breached bund	1	0.2
Procedural breach	A procedure was not followed in the execution of a task	1	0.2
Ore tipped on wrong pile	Incorrect material type was tipped on a stockpile	1	0.2
Failed truck assignment	Truck unable to execute given assignment	1	0.2
Crusher contact	Rock fell from tray and damaged the crusher	1	0.2
Total		432	100.0

3.3 Unconventional incidents driven by new and transformed hazards

The emergence of unconventional incidents types created a new risk profile. A profile that comprised of risks that not only transformed hazards, they formed new ones as well. Transformed hazards were those that existed in manual operations but simply changed shape. Key differences were in pathway to failure and how the trucks approached the situation. For example, 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'.

Driver awareness was entirely removed and replaced with road conditions. It is quite fascinating how the attention had shifted from the person to the environment. Road conditions were always there; however, it appears that truck capabilities were engineered, they were accepted. Load unit interaction remained, simply relocated the consequence. Without drivers, the ergonomics of sitting behind the wheel was no longer the focus. Attention soon turned to road objects and clean-up machines. Since the trucks were not technically capable of distinguishing between objects, the focal point changed to removing the objects. Haul road interactions were remained, however there were no longer radio calls.

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Trucks passively remained in idle or sounded a subtle beep sound on the in-cab display to warn operators. Fixed lanes into the crusher remove the risk of striking the structure. The repetitive nature of reversing a truck was removed; however, it was replaced with remote operations occasionally overriding the system manually.

Table 3. Manual truck hazards associated with incidents

Hazard Type	Description	Associated with incident (#)	(%)	Transformation [b]
Manual truck hazards associated with incidents (removed or transformed hazards)				
Driver awareness	Driver unaware of situation	140	24.73%	R
Load unit interaction	Heavily loaded or struck by excavator	107	18.90%	T
Truck ergonomics	Seating and steering arrangement	88	15.45%	R
Haul interaction	Truck interaction with haulage class	78	13.78%	T
Road conditions	Rough, wet or slippery conditions	32	5.65%	T
Plant interaction	Structure contact can cause truck damage	25	4.41%	T
Boarding ramp interaction	Ramp used to swap out truck drivers	20	3.53%	R
Heavy loading	Large rocks dropped from height	18	3.18%	R
Light vehicle interaction	Truck interacting with small vehicles	15	2.65%	T
Diesel fumes	Fumes airborne in truck cab	9	1.50%	R
Mechanical breakdown	Base truck mechanical problem	6	1.06%	T
Road maintenance interaction	Interaction with equipment working on road	5	0.88%	T
Changing crush lights	Crusher lights changing from red or green	4	0.70%	T
Refuelling hose	Contacting or leaving hose attached	3	0.53%	T
Clean-up machine interaction	Clean-up machine moving around in loading area	3	0.53%	T
Oversize material	Large rocks block crusher or damage truck	3	0.53%	T
Material logging	Material is identified incorrectly (ore vs waste)	2	0.35%	T
Open edge	Exposed height with windrow protection	2	0.35%	R
Access and egress	Climbing up and down truck access ladders	1	0.17%	T
Airborne dust	Dust inside truck cabin	1	0.17%	T
Procedure knowledge	Driver unsure of traffic procedure	1	0.17%	T
Falling material	Large rocks fall out of the tray onto the road	1	0.17%	T
Tyre failure	Ruptured tyres from use or heat	1	0.17%	R
Machine simulation	Simulation working environment	1	0.17%	R

[b] **Key: R = Removed, T = Transformed**

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Boarding ramp interactions had been removed, howbeit trucks continued to be refuelled and inspected. Therefore, a person was still required to interact with the truck. Although exposing drivers to diesel fumes in the cab were eliminated. Predefined lanes allowed driverless trucks to be more accurate in parking beside the fuel bay. Injuries continued to be sustained during truck refuelling. Equipment breakdowns had also remained, however technology-based functions were created. Technology had introduced communication loses. Without a network, driverless trucks will immediately stop. This had driven the increase in lane breaches in driverless operations. Where trucks would previously breach AMA's, light vehicles became the centre point. The risk simply shifted to another proponent, hence the increase in zone locking hazards. Material that was dumped into a loading or dumping area was previously not a hazard. However, since the technology had limited vision of dumped dirt, the material must be surveyed into the virtual mine model to determine the boundary. Similarly, non-site aware vehicles cannot be seen in the virtual system, therefore the trucks had to rely upon LiDAR and RADAR technology to detect objects.

Table 4. Driverless truck hazards associated with incidents

Hazard Type	**Description**	**Associated with incident (#)**	**(%)**	**Transformation**[c]
Driverless truck hazards associated with incidents (new or transformed hazards)				
Road condition	Wet and slippery road conditions	116	26.62%	T
Clean-up machine interaction	Clean-up machine moving around in loading area	66	15.28%	T
Road obstacle	Truck detects windrow or rock	47	10.88%	N
Communication loss	Truck loses communications	38	8.65%	N
Haul road interaction	Truck interacting with haulage class equipment on road	29	6.71%	T
Load unit interaction	Truck being loaded heavily or struck by excavator	27	6.25%	T
Road maintenance interaction	Truck interacts with equipment working on road	22	5.09%	T
Operator awareness	Manual equipment unaware of truck presents	20	4.63%	T
Non-surveyed material	Material not surveyed into mine model	7	1.62%	N
Zone locking	Virtual zones not in place or applied properly	6	1.39%	N
Speed zones	Zones triggering significant truck speed decrease	6	1.39%	N
Non-site aware equipment	Equipment loses escort and does not have a predicted path	6	1.39%	N
Light vehicle interaction	Truck interacting with small vehicles	5	1.16%	N
Technology breakdown	Technology hardware breakdowns	5	1.16%	N
Full dump spot	Dump location already has material	4	0.93%	N
Stationary truck	Truck stationary on haul road	4	0.93%	N
Icon spin	Icon in virtual system flips to cause truck reaction	3	0.69%	N
Truck assignments	Truck loses assignment or lifts tray in loading bay	3	0.69%	N
Tyre separation	Tyre has separated from rim	2	0.46%	T
Single lane access	Virtual system moves trucks into oncoming lane	2	0.46%	T
Machine bubble	Virtual safety mechanism causing trucks to brake instantly	2	0.46%	N

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Table 4 (cont). Driverless truck hazards associated with incidents

Hazard Type	Description	Associated with incident (#)	(%)	Transformation [c]
Material logging	Material type in truck does not match the system	2	0.46%	T
Mechanical breakdown	Base truck mechanical problem	2	0.46%	T
Refuel hose	Lifting refuel hose resulting in injury	1	0.23%	T
Survey mismatch	Virtual mine planned on wrong survey	1	0.23%	N
Changing crusher lights	Lights changing from red or green	1	0.23%	T
Full dump	Truck tips on full dump and material reels over windrow	1	0.23%	T
Fixed plant interaction	Truck recovered and manually tipped contacting crusher	1	0.23%	T
Spot point behind material	Tipping location placed over edges	1	0.23%	N
Oversize material	Large rocks block crusher or damage truck	1	0.23%	T
Rotating technology	Rotating LiDAR system potentially contacting technician	1	0.33%	N

[c] Key: N = New, T = Transformed

Matching the virtual world to the physical world has never been more important. Mining equipment could operate if manual fleet management system was inaccurate. However, in driverless systems, the risk is that trucks can reverse over physical objects once cleared. Even open edge risks to truck drivers has been taken away, it is been replaced with virtual dump locations behind windrows. This has the potential for trucks to reverse over windrows to find the location. However, what is the real risk though? There is no one in the truck? The point here, is that it's not the consequence in isolation, it's the systematic breakdown between human and machine. If the breakdown was connected to another situation, it is imaginable the implications that could emerge.

4. DISCUSSION

The analysis of driverless truck incidents offers some remarkable insights. Over the four-year transition period from manual to driverless control, the technology revolutionised the mine's risk profile. Although the value proposition for automation highlights a direct contribution to safety, the emergence of new hazards and risks remain. It appears that the WA Mining Industry is yet to fully understand the safety risks that driverless technology can introduce. Since the occurrence of a number of unconventional situations (Department of Mines and Petroleum, 2014), there are signs that the industry is starting to rethink how it approaches the expansion of driverless technology. This empirical research will enable the industry to improve their safety systems and leverage the lessons from this mine site.

The original assumption was that the replacement of drivers would eliminate the safety risks of truck driving. Removing the driver from behind the wheel gave the impression that technology took care of concentration lapses and fatigue-related events. This may have been the case, as driver awareness was found to be the most predominant hazard in manual operations. At the same time, however, as the site removed one conventional hazard, technology was simply introducing another. Shifting the most common hazard from driver awareness to road conditions. Therefore, the allocation of driving functions to a machine did not underpin the popular notion on safety. Without truck drivers behind the

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wheel, the mine site did however, achieve a reduction in haul truck incidents. Those incidents were also less frequent given the hours driven by both operations. Personal injuries in operations were almost non-existent, however the three injuries highlight how humans still interact with haul trucks in an operational context.

The transition saw a frequency reduction in haul truck incidents through an uplift in operating hours and reduction in incidents. The uplift was due to a natural expansion of the operation, while the reduction in incidents were realised through removing exposure and engineering elements of the haulage process. For example, automation removed exposure to vibration, sudden seat jolts and tray impacts. The permission-based control system coordinated truck interactions, increased travel lane accuracy and removed the need for associated infrastructure. Coordinating truck movement removed priority rules breaches and traffic management non-compliances. Specific travel paths avoided material contact, refuel hose damage and reversing into the crusher when tipping. All of which, made significant contributions to improving the mine site's safety performance. However, as conventional incidents were being removed, technology was in the process of exploiting residual risks and cultivating some of its own.

The introduction of unconventional incidents should be addressed with caution. Particularly in how they evolved and what appeared to be 'normal operations'. It was not a simple broken part; it was a complex human-machine interaction trying to achieve a goal: moving dirt. Technical limitations of driverless technology saw support roles locally adapt to keep the wheels turning. This was evident in the application of speed zones, road obstacles clearances and truck reassignments. Design parameters had neatly threaded humans along the fringes, creating a system that leveraged human redundancy to overcome non-design situations. Engineering capability coupled with residual tasks created a new system of work. A system that only expected what had been engineered. Human tasks were therefore filling in the gaps and learning through practice. Learning that driverless trucks needed speed zones in wet weather, clearance to proceed passed obstacles and new assignments when instructions were irrelevant. As a consequence, the risk profile extended beyond functional models and failure modes. It was a complex arrangement between driverless capability, residual work processes and the frontline joining the dots.

5. CONCLUSIONS

Despite the original assumption that safety risks could be eliminated through haul truck automation, this research highlights that the technology is not there yet. It is evident through the emergence of a new risk profile that was explored in this study. The risk profile is considered new when comparing the hazards and risks of a manual truck operation. Hazards were reflected in the incidents involving driverless trucks, which were unique to automated operations, due to novel pathways and situations that emerged through its introduction. This pinpoints the significance of identifying the safety risks when introducing driverless technology into a mining operation.

Significant progress has been made on removing human exposure to high-risk tasks. Automation was successful in reducing injuries to frontline personnel and coordinating the interactions between haul trucks. This highlights the value proposition of haul truck automation to the mining industry. It must be noted, however, that the industry cannot become complacent. Results of this study clearly show mining companies must truly understand the capabilities of the system they are using. Improving their user knowledge in not just how to work automation, but truly understanding how driverless trucks work. This will allow them to work more closely with the system and improve the transparency between human and machine.

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Based on the results of this analysis, it is recommended that WA Mining Industry, in particular, review their relevant Guidance Notes and Codes of Practices to reflect the hazards and risks that were outlined in this study. Modern innovation in safety practices need to be implemented to assist mining companies to thrive in this digital revolution. The automation of haul trucks is just one example, however the principles on human-machine collaboration can applied more broadly. An example would be explaining the importance of matching the physical mine to the virtual model. There are necessary steps in physical verifying digital models before automated equipment is clear to proceed. Developing new work practices can allow mining companies to redesign their safe systems for this next phase.

This study was based on the haul truck incidents that occurred on a mine site in WA. The fact that it was only conducted on a single mine site, with one product, is a limiting factor. There are increasing number of automated systems working across Australia. Despite incidents being an indication of possible breakdowns in the system, it may not have recorded all breakdowns that can result in an incident. In addition, the incident descriptions were interpreted to the best of the researchers' knowledge. As a consequence, incidents could have been grouped or labelled different to reflect the data. Moreover, not every haul truck incident may have been reported. Nonetheless, there is large sample size to allow the research to draw conclusions, with each incident and hazard type that were used to inform the study's findings.

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AUTHORS

Dr. Todd Pascoe, MOccMedHlth&SaF, is a Business Improvement Specialist in the Western Australian Mining Industry. Todd has worked in the Western Australian Mining Industry for over 10 years in specialised roles across Health and Safety, Mining Production and Business Improvement. Todd has extensive operational experience in the deployment and day-to-day running of an autonomous haulage system, including the development of risk assessments, health and safety systems and operational efficiencies.

Dr. Shirley McGough, RN, MHN, Dip App Sc, BSc (Nursing), PG(Nurs), MNurs, PhD, Senior Fellow, Higher Education Academy. Shirley currently works at Curtin University and teaches mental health, behavioural and biosciences, conducts research and evidenced based practice. Shirley has extensive clinical and research experience in mental health and wellbeing, with substantial educational and leadership experience in the University sector.

Dr. Janis Jansz, RN, RM., Dip. Tch, BSc. Grad. Dip. OHS, MPH, PhD, FSIA is an Associate Professor in Occupational Health, Safety and Environmental Health in the Western Australian School of Mines: Minerals, Energy and Chemical Engineering at Curtin University in Western Australia and is a Professor at the Xi'an University of Science and Technology, China. She also works for the Healthforce Group. Janis is the Director of the World Safety Organization National Office for Australia and Vice President of the Occupational Health Society of Australia. She has been awarded Life Membership of the Australian Institute of Health and Safety for many years of work improving, teaching and conducting research to advance occupational safety and health practices and for taking a leadership role the safety and health profession.

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