Mine Planning and Selection of Autonomous Trucks

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Abstract. Autonomous trucks achieve greater productivities (up to 30%), and do so with reduced fuel, maintenance and tyre wear. This is in addition to the lower costs for personnel, offset by costs of communication networks and control room operators.

This paper discusses the mine planning and selection of rendering trucks autonomous, including:

- What is an Autonomous Haulage System (AHS) and how they work;
- What changes in the mine design process;
- How does the mine planning and scheduling change;
- What are the benefits, both perceived and actual from implementing an AHS;
- What are the selection criteria, and how does a mine site make the decision to implement an AHS; and
- The decision-making process to complete the path to automation.

The paper will also summarise the current status and future state of general vehicle automation in the mining industry.

1 Introduction

Automation is an emerging key value driver within the mining industry. Automation was used extensively within mineral processing and metallurgical functions prior to even the use of solid-state electronics. However, Autonomous Haulage Systems (AHSs) only began field testing in open pit mines in the early 1990s. Commercial adoption happened nearly 20 years later in 2008. Technologies for vehicle autonomy advanced rapidly in recent years, which has moved the automation of mining fleets within reach of many mining operations.

On-board systems of an Autonomous Haulage Truck (AHT) are similar to other autonomous vehicles including a Google Car or Tesla's system (Fig. 1). An autonomous vehicle system requires a vehicle control unit that takes in sensory perception,

E. Topal (Ed.): MPES 2019, SSGG, pp. 203–212, 2020.
https://doi.org/10.1007/978-3-030-33954-8_26

communication, and outputs the appropriate vehicle controls to the actuators within the vehicle system.

Typical sensors utilized in autonomous vehicles include:

- Radar
- LiDAR
- High Precision GPS
- Cameras
- Odometers
- Inertial Measurement Units (IMUs)

Typically, actuators utilized in autonomous vehicles are already onboard a manned vehicle. They are accessed via a Controller Area Network (CAN) bus, which is an internationally accepted standard designed to allow microcontrollers and devices to communicate with each other in applications without a host computer. Most modern on and off-road vehicles are primarily drive-by-wire devices. They take inputs from a sensor that the operator/driver controls and then electronically control the vehicle functions such as steering, throttle, and braking.

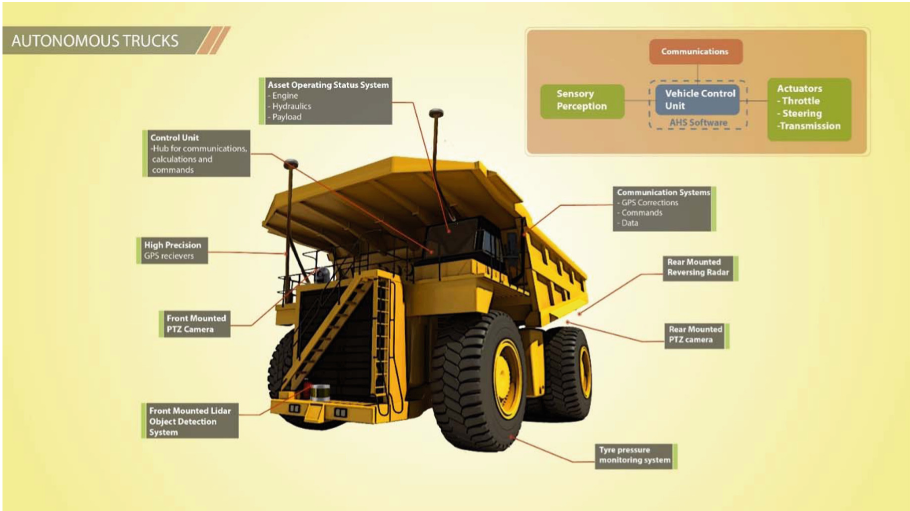

Fig. 1. Generic AHT onboard AHS equipment (Miller 2016).

AHSs are more than trucks and onboard sensors. AHSs consists of:

- Mining trucks equipped with commercial and proprietary electronic devices.
- Software to command, control and track vehicle movements and interactions.
- A communications network with complete coverage to all active mining areas.

- High precision Global Positioning System (GPS) transponders.
- A team of control room operators and site support staff to manage vehicles, devices, and the network.

Integration of AHSs at a mine is a complex task that includes many of the safety hazards of a conventional surface mine as well as the specific safety risks associated with AHSs. Prior to implementation of an AHS, risk analysis and risk mitigation must be undertaken during development of the system and must continually occur during the commercial operation and improvement of AHSs.

AHSs are operating safely and effectively within the Pilbara region of Western Australia for over a decade. Safety incident and accident data show very few events have occurred and are primary limited to human errors such as failing to yield to traffic or follow operational procedures.

2 The Economic Case for AHS

AHS conversion from a manned fleet is most easily described as a CAPEX (capital expenditure) to OPEX (operating expenditure) trade off. Current AHS sites see significant unit cost improvements over a manned site. The principal benefit of AHS is increased productivity in the AHTs due to increased utilization. Typically haul trucks in an open pit mine are scheduled for 5,000–6,000 h per year. AHS sites achieve significantly higher utilization rates that can result in annual scheduled operating hours of 7,000 h for AHTs. This is an increase of 16–20%.

> *"Rio Tinto's autonomous fleet accounted for about a quarter of the total material moved across our Pilbara mines. On average, each autonomous truck was estimated to have operated about 700 h more than conventional haul trucks during 2017 and around 15% lower load and haul unit costs."* Rio Tinto Media Release *(RTIO* 2019*).*

> *"AHS trucks have moved over half a billion tonnes of material and have achieved a greater than 30% increase in productivity levels."* FMG Media Release *(FMG* 2018*).*

Increases in utilization and operating hours are due to the reduction in variability that is achieved through the deployment of AHS. James Petty presents an effective utilization analysis in his 2017 AusIMM Bulletin article. His comparison shows how the removal of variability due to truck operators, removal of shift changes, removal of breaks, and the impacts of surging and queuing can vastly improve the consistency and efficiency of a haul truck fleet. Improved consistency through the introduction of machine control has the effect of transitioning the mining environment from managing discrete components, such as people, to managing a continuous process (Fig. 2).

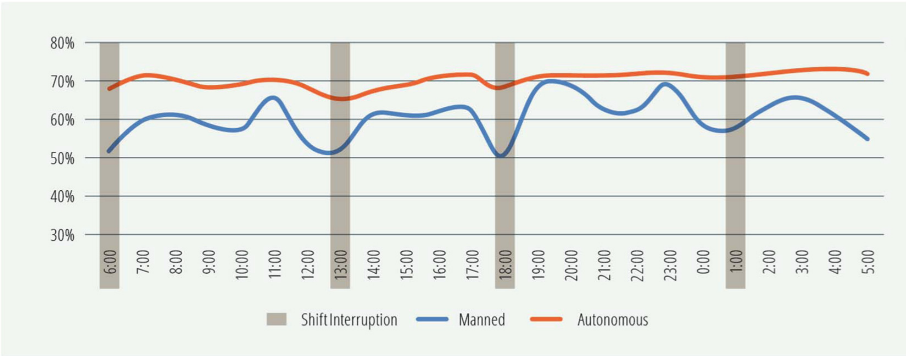

Fig. 2. Effective Utilization curve showing manned versus autonomous vehicles. Adopted from (Petty 2017)

Additionally, the cost to operate an AHS truck is reduced from a manned fleet and reflects a reduced operator count at the mine.

> *"If you think about a manually-operated truck, you need about four-and-a-half people. That's the metric that we've used to help articulate not only the safety component but also the economics behind labour. Within the last month we've dropped below 0.8 people per truck." –* Craig Watkins, Caterpillar commercial manager for a surface mining technology 2018 *(McCrae* 2018*).*

However, cost savings are not only limited to a reduction in operators. AHS fleets are experiencing reduced fuel consumption, reduced maintenance costs, and extended tyre lives.

> *"These autonomous trucks, by the way, have reduced fuel use by 13 percent and hence improved environmental performance by 13 percent."* Bill Walsh, former CEO of Rio Tinto Iron Ore, 2018 *(Barbaschow* 2018*).*

Mine sites implementing AHS typically achieve significantly longer tyre lives. In the manned Pilbara mines, typical tyre life budgets are 5,000 h at a manned operation while autonomous mining operations can potentially budget a 7,500 h tyre life. This extended tyre life benefit results from several factors at AHS sites:

- AHTs only operate on a programmed route.
- Vehicle collisions are greatly reduced.
- Impacts to rocks are reduced.
- Sidewall punctures due to rubbing tyres is greatly reduced.
- Wheel slip is nearly completely prevented due to AHS control.
- AHS sites have rigorous road maintenance programs to ensure AHS can operate unimpeded by hazards such as pot holes, water run-off pathways, and washboard road (Fig. 3).

Fig. 3. AHT tyre at retirement (Price 2017)

3 Mine Planning for AHS

Mine planning for an AHS mine is almost identical to a non-AHS mine. The single critical difference is that the haul roads are approximately 15% wider than a conventional mine, which results in a slight decrease in the overall slope angle of the mine wall. The batter angles, berms and catch bench width can remain the same.

A common truck utilised in many of the existing AHS installations is the Caterpillar 793F. A typical Caterpillar 793F is approximately 8.3 m wide. A typical haul road in a non-AHS mine is 3.5 Truck Widths (TW) wide, making a haul road for this truck 29 m wide. A haul road for a 793F on an AHS system is 32–34 m wide making it approximately 4 TW's wide. This increase in width of the road is due to the object detection system, which is less likely to produce a false positive from objects on the side of the road when they are wider (Fig. 4).

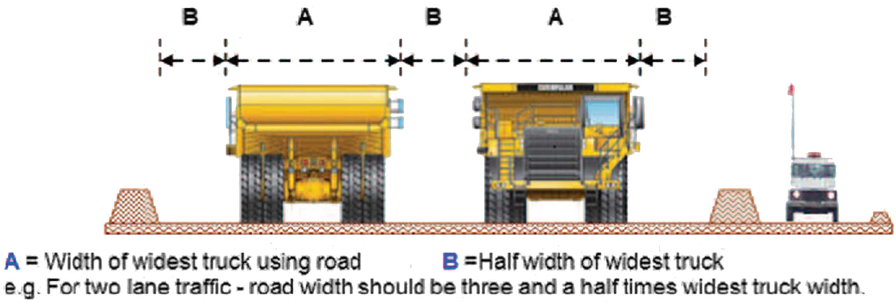

Fig. 4. Haul road truck widths (H&SA 2019)

Another minor difference to mine planning on an AHS site is that the windrow is pulled back from T-Intersections by 10–20 m. The purpose of this is so that the sensors do not think the windrow is an object when the truck is turning or driving past the windrow, and therefore halt the truck (via the Object Detection System). Dump designs for an AHS system are practically identical to that of a normal mine. The trucks prefer a higher overall (waste) dump; this is because their on-board communications systems benefit from the increased height.

4 Perceived and Actual Benefits of Implementing AHS

The clear perceived incentive in making any system or process autonomous is the associated increase in safety and efficiency, increasing the profit margin through lower cost and greater productivity. Implementing AHS is no different. While having a high initial cost (as discussed below), implementing AHS has a definite long term gain with productivity improvements of around 15-20%, along with maintenance savings, tyre life and equipment improvements and significant safety benefits (Bird *et al.* 2019).

The predictable nature of autonomous systems allows for the lifetime of a machine to be planned from implementation to the end of life of the machine, including downtime due to maintenance. This allows a cost analysis to be accurately implemented to compare the difference between autonomous and non-autonomous systems. While the cost benefit varies for each mine site, productivity due to machine utilisation has been increased by about 21% through a study on actual autonomous truck data (Brundrett 2014). The obvious advantage is the decrease in downtime due to human activity, such as breaks, shift change and accurate dispatching. With the need for an operator alleviated, the cost in staff is reduced per truck with each truck optimised for operation, with one or two supervisors capable of managing an entire fleet. Typical shift personnel are reduced by a headcount of 4, with an increase in technical and operating staff of about 1 (Bird *et al.* 2019). In addition, the wear on the machine is also predictable allowing maintenance to be scheduled accurately for machine wear and tear due to optimal driving and performance of the machine.

As mentioned above, one of the main advantages of autonomous systems is an increase of safety within the autonomous zone. There are several factors to why autonomy increases the safety of a mine site, such as;

- Removal of personnel (and therefore human errors and associated hazards) from autonomous zone
- Increased and shared awareness of obstacles
- Predictable nature and path of machinery

The obvious advantage in making a system autonomous is the removal of any staff in the autonomous zone, creating an environment where if any incidents were to occur, injures would be avoided. Most accidents are caused due to fatigue, stress and lack of competency of an individual. AHS remove human error and judgment, relying upon the overall network and individual sensors mounted on each truck to guide the vehicle and avoid collisions. The ability to rely upon multiple sources greatly increases the accuracy and precision of the vehicle, allowing navigating and avoiding accidents before line of sight confirmation is achieved. Caterpillar, one of the leading manufacturers of autonomous mining equipment, boasts zero lost-time injuries from 27.3 million kilometres driven across 5 years of their autonomous trucks (Harry 2018).

With the addition of 'smart' systems, trucks can be updated with improved predicted pathways capable of navigating around obstacles in real time. This creates a stable, overall greater net income with a higher yield per hour than previously manned systems, with 7 autonomous trucks hauling the same quantity of ore as 9 manned trucks (Brundrett 2014). In addition, the expected behaviour of autonomous trucks and how they respond in certain situations allows for pre-determined responses, potentially before an incident occurs.

5 Negatives Associated with AHS

Just as there are many perceived benefits of implementing AHS onto a mine site, there are also many perceived negatives associated with both the idea of autonomous technology and the implementation of autonomous systems. As with most technological upgrades, there are a multitude of initial costs that must be accounted for with the implementation of a new system. AHS is no different.

AHS key components:

- Mining trucks fitted with both commercial and proprietary electronic devices.
- Software that commands, tracks and controls vehicle interactions and movements.
- Communications network (both hardware and software) with network coverage to all areas.
- Control room operators and support staff managing and maintaining the vehicles and associated systems.

Once AHS has been implemented onto a mine site, higher costs are associated to the increased use of graders and dozers that now have a higher run time. General maintenance costs also increase with faster wear and tear of the vehicles due to the increased operating run time. A flow on effect is made from this, with roads also having to be maintained at a greater frequency. In addition, the continual upkeep of the network and software license fees also add an increased ongoing cost.

With mining making a move to increased implementation of autonomous systems, the role of operators is made redundant, however the experience required for assisting in programming appropriate responses to the environment is of high value. While there is an added benefit of employment in support staff, training must be undertaken for support staff and any staff that may be required to access autonomous areas, with the associated training costs included.

A mine conversion to an AHS system is a slow process and the ramp up time of the system is generally around 12 months in which the utilisation of the trucks will slowly increase over this time until it reaches the highest possible utilisation. The main reason for this is the site-specific programming of the AHS system which includes haul routes, load locations and dump locations. The site must learn the most efficient way of programming an AHS system that utilizes the site resources optimally. The next reason is the training of the mine staff, where the AHS operators, pit crew ("pit patrol"), AHS Technicians, loading unit operators and maintenance staff require extra training in order to be able to work effectively around an AHS installation. The final reason for a slow ramp up is the required cultural change of the site, once the site is used to AHS, the system will run smoother.

Social impact of autonomous systems is significant, with potential adverse community and government mindset constraining the uptake of the technology and increase implementation costs (Moffat & Zhang). One perceived negative regarding AHS is the safety of personnel and equipment within autonomous zones. This perception, while mostly just perception, creates its own issues as the world and workforce adjusts to the ideas associated with autonomous mobile equipment. Autonomous equipment allows for human error to be decreased, however this error cannot be fully negated. Horberry and Lynas (2012) state that while operator acceptance, up-skilling, user-centred design and integration are of key importance, trust is also required for the technology to be effective. One only has to look at previous technology that has been implemented but phased out due to adverse public opinion. The super-sonic Concorde for example, met with negative public opinion after a safety incident occurred, resulting in the aircraft ceasing production and implementation. A similar incident may result in the same outcome for autonomous systems. Therefore, positive press, and public workforce opinion is of high importance for this industry to succeed.

While the safety concept of an autonomous system is to negate the need for direct human interaction, due to unforeseeable circumstances or general maintenance on site, some human interaction is required to maintain the system. This is the greatest concern for safety as the autonomous system needs to be navigated safely in order to accomplish manned tasks, creating a risk for autonomous and manned interaction to take place. The development of 'Site Awareness Systems' or 'GPS-Equipped Manned Vehicles' and 'Autonomous Emergency Stops' aim to provide safe passage into the autonomous zone through creating a safe 'bubble' around the manned vehicle, which interfaces into the autonomous network. This alerts autonomous trucks to the presence of a manned vehicle and provides the safety criteria that the truck must meet. As the name suggests, the Autonomous Emergency Stop shuts down any local autonomous machines in the case of an emergency. Both of these are in addition to the peripheral sensors mounted on autonomous trucks.

Unfortunately, a potential negative of making one part of a system more efficient is the flow on effect causing the transfer of stress onto other areas. What was once the choke point within the mine system has now been transferred over to other sections, such as the processing plant. While the increase of efficiency is not necessarily a negative aspect, it does create stress on other areas that may be restricted either by human or machine operating factors or both. This may require future upgrades or be the limiting factor in the productivity of mine sites as they strive for the most economical and efficient system.

6 Current and Future Status of Mining Automation

Currently the state of AHS in the mining industry is in a transformation stage where Original Equipment Manufacturers (OEM) and automation companies are reporting that AHS is going from a push to a pull.

> *"One of the key changes that's happened over the last year or so is that we have gone from a push scenario where we've been trying to educate the industry of the value and the benefit of automated hauling solutions" – Craig Watkins, Caterpillar commercial manager for a surface mining technology 2018 (McCrae 2018)*

This means that AHS manufacturers aren't having to push their product on customers anymore, but the clients are coming to them for their product. This signals a major change in the mining industries outlook on AHS, that the proven improvements and results from the pioneers of AHS have made other companies see the benefits.

Due to the price of automation dropping, the price of labour increasing and the proven increase in safety (Amin 2018) the amount of companies interested in AHS and the number of manufacturers producing AHS systems has increased in recent years with smaller companies announcing their plans to invest in AHS. Soon AHS will be manufactured by more companies, bought by more customers and be implemented in more countries than ever before. Moving it from a niche product that only the big mining companies can afford to an essential commodity and in the future, the standard for mining.

Mining companies are already planning their mines around AHS, which will soon be the standard for mining. This means mine planning, infrastructure, vehicles and AHS specific operating areas will be designed into a mine from the beginning rather than it being a retrofit on an existing mine.

Automation of other mining equipment is the next step in automation in the mining industry with the next biggest hurdle being the automation of diggers (Stevens 2019). The challenges here will be ensuring the autonomous diggers don't overload or underload the trucks and that they do not slip off benches being mined.

Acknowledgements. Acknowledgements to Aidan Ayres of AMC Consultants for assistance with this paper. We further acknowledge our clients and their dedication to technology investments.

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