AUTONOMOUS VS MANUAL HAULAGE TRUCKS - HOW MINE SIMULATION CONTRIBUTES TO FUTURE HAULAGE SYSTEM DEVELOPMENTS

Juliana Parreira, John Meech

Norman B. Keevil Institute of Mining Engineering,
The University of British Columbia, Vancouver, BC, Canada, V6T1Z4

Corresponding author: (jpareng@hotmail.com)

Abstract
The past decade shows record increases in global demand for minerals and metals with an accompanying significant decline in skilled personnel. Mining companies today are examining new technologies to maximize production, reduce costs, and create safer work conditions to deal with this shortfall. Automation of an open-pit mine haulage system is receiving attention as a beneficial option since it provides more consistent and efficient operation of mining equipment, it removes workers from potential danger, it reduces fuel consumption significantly reducing greenhouse gas (GHG) emissions, and it can help optimize vehicle repairs and equipment replacement because of more-predictable and better-controlled maintenance. This paper describes a simulation model under development using the EXTENDSIM software package to examine scale-up issues and constraints of autonomous vehicles in comparison to a manual system. The software can predict and manage Key Performance Indicators (KPIs), such as productivity, safety, cost, equipment failures, fuel consumption, and tire wear under different road and load conditions. By breaking-down the various systems of an autonomous haulage truck and simulating the overall haulage system using a Monte Carlo approach, the model becomes a flexible and powerful tool to use within a mining organization. Direct comparison to a manually-run system can be done to show the cost and operational benefits of automation. Project managers can use this tool to guide decision-making about possible application of autonomous haulage trucks at a specific mine site.

Keywords: Discrete Events, KPIs, mining industry, management, autonomous haulage trucks.

Growth of Automation
Today’s organizations face many challenges: demanding customers, global competition, and currency fluctuations. As a result, organizations are looking for automated processes to improve efficiency. According to a study conducted by the ARC Advisory Group, (a leading organization
in manufacturing, logistics, and supply chain solutions) process automation systems are expected to grow globally by 9.6%, at a compounded annual growth rate with an contribution of over $47 billion by 2011 to the world economic markets. Asia is leading in large automation projects, with China driving the global demand [1].

Globalization is the main factor that compels growth of process automation systems, because as opportunities and partnerships expand there is increased complexity around the management and distribution of diverse products and markets. Competition has heightened and successful companies require improved efficiency, product-quality monitoring, product and equipment availability, employee safety, flexibility, and delivery performance. To this end, it is important to incorporate automation into the organizational processes of an enterprise since one of the main characteristics of an automation system is rapid response to environment changes.

**Definition of Automation**

The Oxford English Dictionary (2005) defines automation as the use of machines to do work that was previously done by people: so automation is often interpreted as the loss of jobs [2]. Parasuraman et al. defines automation as the full or partial replacement of a function previously carried out by a human operator [3]. These two definitions suggest that the objective of automation is to control the behaviour of dynamic systems and emulate physical and intellectual human capacity. There are several degrees of automation and these can be simplified into the following categories: direct control, supervisory, automatic and autonomous systems, where there is less human intervention during the operation with each successive degree of automation [4].

Mining automation has employed direct tele-operation; for example, workers control the mining process using a computer in a control room; remote operation; for example, drilling is performed by workers using joysticks from a distance; and autonomous; for example, open pit/underground autonomous haulage trucks with no human intervention.

Although the Oxford Dictionary definition claims the main focus is worker replacement, as Bibby et al have pointed out even highly automated systems during the 1975 energy crisis, such as electric power networks, needed human beings for supervision, adjustment, and maintenance. So, one can draw the apparently paradoxical conclusion that automated systems are man-machine systems for which both technical and human factors are extremely important [5]. Automation
does not always result in people replacement; on the contrary, it can elevate human capacity into higher level decision-making. Whatever the case, workers need a different set of skills to handle the specialized tasks related to automation and the new technical challenges.

*Autonomous Haulage Trucks (AHT)*

In mining, automation is playing an increasingly important role due to the scarcity of high demand metals; challenging locations and harsh environments becoming the norm. As a result, automation is being used increasingly throughout the industry from underground to open pit mining in order to increase process efficiency, safety, and production.

Due to advances in automated tracking systems, control equipment, telemetry and robotics, there are major improvements expected in the precision and safety of mine machinery. As a result of these advances, driverless haulage trucks are now being developed for open pit mines. Wireless communication, object-avoidance sensors, on-board computers, GPS systems and artificial intelligence approaches enable haulage trucks to drive themselves, or to be driven by an operator at a control panel well-away from any danger [6].

Komatsu and Caterpillar are the two companies responsible for autonomous haulage truck development. Komatsu is already using this technology in Rio Tinto’s Pilbara mine, an iron ore mine located in Australia. In December 2008, Komatsu’s FrontRunner Autonomous Haulage System started trials at this mine with driverless trains and trucks controlled from Perth, 1,300 kilometres away. All truck navigation at the mine is remotely controlled [7]. At the Codelco/Rio Tinto Gabriela Mystral mine located in Chile, a second Komatsu project has been installed [8].

The Caterpillar autonomous haulage truck project is a joint-venture project with BHP-Billiton. As part of the alignment, Cat and BHP Billiton are launching joint autonomous mining haulage development programs. The companies’ development program includes enhancing the existing mining trucks by integrating them with robust autonomous sub-systems many of which are Caterpillar technologies already proven in the marketplace. The companies plan to have autonomous trucks at selected mine sites by 2010 [10].

Autonomous haulage trucks contribute greatly to reducing losses associated with human elements such as individual performance, personal breaks, and absenteeism [9]. While driverless haulage
trucks are not immune to breakdowns, increased consistency and scheduled maintenance will increase the lifetime of machine components, leading to longer periods between maintenance, and therefore reduced costs associated with maintenance. Lost production can be minimized or eliminated as unpredicted breakdown frequency declines [10]. Lost time is not always accounted for as a specific cost since mines often contract equipment in order to meet production targets. Fuel consumption is reduced when a truck is driven in a stable, consistent manner. Drivers perform well at the start of a shift but as fatigue sets in towards the end of a shift, their performance varies considerably. By reducing fuel use, greenhouse gas emissions, and operating costs, autonomous haulage trucks directly contribute to the principles of sustainability.

Statistics reveal that using autonomous haulage trucks in an open pit improves safety, maintenance and equipment life, optimizes fuel consumption, and provides streamlined operations with increasingly accurate production systems. But even with these advances, mining companies must work hard to connect this new technology to other organizational processes. The decision to implement an autonomous process in a mine must consider all possible impacts, not only operational improvements.

Implementation Strategies

The success of an automation project depends on good implementation strategies, commitment and vision of the organization, and sponsorship. It is important to identify the Major Critical Success Factors (CSFs) related to an autonomous haulage truck project. Examples of CSFs to describe an automation project are as follows:

- Formulation of a simplified and standardized project plan prior to project design;
- Assembly of personnel teams with the necessary experience and motivation to properly implement the system;
- Development of the functional structure of operations, maintenance, and management as modular units;
- Effective communication within these functional groups and documentation that clearly spells out the plans and objectives;
- Evaluation of the performance of the system and modifications done to keep it operating efficiently.
The use of a Balanced Scorecard (BSC) is a tool that allows an organization to devise and monitor CSFs enabling the successful implementation of a complex project [11]. A BSC evaluates an organization’s performance in a number of different areas with the objective to align new business activities to the existing and new visions and strategies. It assists in improving internal and external communications, and in generating continuous monitoring of performance.

AHS will be successfully accepted in a company and across the industry if the Balanced Scorecard shows clearly how the CSFs link to performance measures of project phases such as implementation, start-up, and operation. Knowing how to monitor performance measures, especially throughout transitional and implementation stages, is important. An organization must monitor and assess these indicators continuously since variable results will impact and/or develop best-practices for decision-making, organizational strategy, quality-control, measurement, and reporting improvement trends of the performance indicators (PIs). Certain indicators are key to the bottom-line aspects of the overall project implementation and success (KPIs) while others are essential in anticipating future problems and necessary changes.

To this end KPIs that represent the set of selected measurements must focus on critical performance aspects. They must be analyzed and monitored on a regular basis to quickly identify output changes that emerge as a result of any technological changes. In implementing an Autonomous Haulage System, for example, it will be useful to know the degree (or level) to which a robotic system can approach or exceed the productivity of a manual system as well as the control factors that affect productivity.

**Importance of Predicting KPIs**

To predict the level of improvement of AHS, simulation software that analyzes the behaviour of this new technology can be used to study possible changes in adaptability and utilization. Komatsu uses software called Modular's Dispatch® system that categorizes haul truck time into five major categories: ready, down, delay, standby, and shift change. From these classifications, key performance indicators such as haul truck fleet utilization may be calculated [12].

KPIs are not past indicator measuring events [11] and so, simulation software help to predict benchmarked KPIs as well as discover new ones that might characterize changes from new
technology. This will quantify improvements and enable decision-making, i.e., the level of improvement to justify the cost and benefits of the technology.

Technology alone is only one piece of a complex solution to improve performance. Significant benefits will be achieved when technology, processes, and possible challenges are integrated with the key success factors and performance measures used to guide planning and management. Failure to properly incorporate success factors and KPIs may result in failure of the system or faltering authorization from top management. To this end, offline simulation software that allows prediction and comparison of KPIs according to autonomous and manual haulage systems should be incorporated into the project.

The main purpose of simulation is to improve the technology and make sure that the autonomous haulage trucks adapt smoothly to the organizational process, adding value. The software can show the cost and operational benefits of automation and in cases when autonomous trucks KPI changes are unexpected, it can be used to develop improvements in system utilization. In addition, the tool can help to develop and analyze new KPIs for this new technology.

Simulating AHS allows the determination of overall improvement in the long term across all KPIs. The presence of certain attributes or absence of specific constraints at a particular mine may be necessary to ensure the overall performance improves, i.e., weather conditions, topography, geology, etc., can be studied.

**Simulation Software**

The proposed software consists of two components: supervisory software and model. This paper describes the models used for the simulation which are still under development.

By definition a model is an abstracted and simplified representation of a system at one point in time. Models are an abstraction because they attempt to capture the realism of the system. They are a simplification because, for efficiency, reliability, and ease of analysis, a model should capture only the most important aspects of the real system. Dynamic modeling is the foundation for computer modeling [13]. To this end, the word “model” in this paper describes a particular dynamic behaviour of a system or a process. One of the main benefits of a model is that it begins with a simple approximation of a process that is gradually refined as more detail is examined. As
refinements are added, the model more closely imitates the real-world process across a wide variety of variable changes.

Discrete event modeling is used in our approach, i.e., the system changes state as events occur and only when an event occurs; the passing of time has no direct effect on the model activity or performance [13]. The simulation software consists of two main models: one using only manual trucks and the other using autonomous trucks. By having these two models in the same virtual environment, direct comparisons can be done and interaction studies performed. In addition, a Monte Carlo approach allows relationships and parameters to vary randomly within a distribution of possibilities. This provides a range of results rather than a single output for each test run.

The discrete event models have a set of constraints regarding real-world factors that influence their performance. These parameters include, but are not limited to, climate conditions, haulage road topography, dust, snow, mud, truck-performance, maintenance-scheduling, interaction with non-robotic trucks and auxiliary vehicles, and aspects of the communication network and various sensors. As well independent elements such as shovels, roads, road segments, dumps, digging points, water trucks, cheery pickers, light vehicles, and dozers are being modelled as well.

The simulation models are being built in ExtendSim, a graphical software package that can break a network down into unique components each having specific delays and characteristics with respect to maintenance, speed, fuel consumption, braking, acceleration, etc. ExtendSim has benefits such as ease of use, provision of debugging and error diagnostics, the ability to communicate with other software tools such as spreadsheets and external execution programs. Animations and a graphical environment for visualization of the simulated mining process are also important features.

**Manual Haulage Model**

The manual haulage model includes sub-models to characterize the human truck drivers who must work 12-hour shifts on a 2-week-on/2-week-off schedule with all trucks running 24/7. The manual model is set to account for the performance of different drivers – new and experienced – consistent and inconsistent – recently trained or retrained – ones who tire appreciably at the end of the shift – ones who brake too hard – ones who play tunes on the accelerator consuming excessive fuel – etc.
Due to shift changes, truck and shovel availabilities, individual worker performance, weather changes, mining schedules, and other factors, mine production may change. The manual model will determine the base case against which all other test work will be compared with an initial focus on shift production of material loaded, hauled, and dumped.

In addition to mechanical availability, the manual truck model considers two types of maintenance: Failure and Planned. Exponential and Weibull distribution functions will be used to introduce each type of failure on a random basis with increasing frequency as time passes if planned maintenance is not conducted. The Weibull distribution is an excellent way to model failures from mechanical degradation such as corrosion and fatigue, while other types of failures such as refueling are better modeled using an exponential distribution. Maintenance costs will also be included.

![Figure 1: Weibull probability density](image)

**Autonomous Truck model**

This model is broken-down into various sub-systems or agents of an autonomous haulage truck such as communication, brake, accelerator, steering, positioning system, radar sensors, and other instruments and actuators. to understand the full interactions that may affect autonomous truck behaviour. Behaviours will be studied and analysed for different external environments such as
road conditions, interactions with non-robotic vehicles, climate circumstances, etc. Simulating different autonomous behaviour can generate knowledge to predict how a sub-system (agent) or the overall system can be reconfigured to improve system efficiency when a step (or pulse) change occurs in any system parameter.

Breaking-down the various sub-systems of an autonomous haulage truck and simulating these using a Monte Carlo approach enables a better understanding of system sensitivities to different sub-system variations. Figure 2 shows the possible sub-systems (agent) of an autonomous haulage truck being considered in the AHT model. Direct comparison of a manually-run system with the autonomous one can show the added costs and operational benefits of automating trucks.

**Figure 2:** Sub-systems of an autonomous haulage truck.

**KPIs considered**

Important KPIs from each model will be chosen in accordance with the benchmarking success of the mine. KPIs include productivity, safety, breakdowns, maintenance and labour costs, and cycle times. Additional KPIs that are important during the work include fuel consumption, tire wear and investment per truck. Not all KPIs are likely to improve when automation is introduced. For example, the AHT speed may be limited for safety or technical factors to a level below that of the manual truck, although the variance will certainly decrease. Despite this reduced performance, it is expected this will be balanced by significant improvement in availability, mechanical and
reduced waiting. The overall changes across all KPIs will be compared and the combined effect evaluated. At this stage, the following estimates (or targets) of KPIs differences are expected:

- Investment cost per truck +30%
- Truck haulage cycle times - 7%
- Fuel consumption -10%
- Tire wear -12%
- Mechanical Availability + 8%
- Increased productivity + 5%
- Maintenance costs -14%
- Increased truck life +12%
- Labour costs - 5%
- Improved Safety/Reliability to be determined

Note that the expected improvement in Labour costs is not particularly high. Despite there being no further need for four truck drivers (two on each cross shift cycle) for each truck, additional personnel will be needed to maintain the trucks and their sensor and control sub-systems. These employees will be much more skilled intellectually and thus, will have increased salaries.

**Software Architecture**

With an autonomous haulage truck system, it is important to choose a software architecture that can deal with each element in the system as an "Agent". Each truck, each shovel, each dump, each road section, and all other vehicles in the mine must be considered as independent, interacting Agents. This type of architecture allows maximum efficiency and effectiveness in developing and running the overall software system. It guarantees that access to computer hardware resources follows a consistent pattern that accounts for priorities and maximizes model effectiveness and efficiency.
An agent is an entity that receives requests for services from other agents (who are Clients with respect to the servicing agent). If it is currently inactive, then it fulfills such services. For example, a truck arrives at a loader and requests the loader to fill its bucket with ore. The loader receives the request, processes it to establish a "contract" with the truck, and then fulfills the "contract" by loading the truck.

Another example: a truck arrives at the start of a road segment and requests permission from the main supervisory system to enter the road segment. The main supervisory system (acting as an Agent to the truck) provides such permission and instructs the road segment to allow the truck to enter. The truck enters the road segment and is "serviced".

Each instrument, final control element, motor, switch, light, etc. mounted on each truck can also be considered agents. As such, Agents represent a hierarchy within the system in terms of actions and interactions. This structure permits redundancy since logical inferences can be made about an Agent even when it fails to communicate its performance to the central supervisory system.

A behaviour is a specific action performed by an agent or a collection of agents. For example:

A truck must stop for some reason: Stopping is Behaviour.
A truck must turn left for some reason: Turning Left is Behaviour.
A truck must accelerate for some reason: Increasing speed is Behaviour.
A truck must decelerate for some reason: Decreasing speed is Behaviour.
A truck must back-up for some reason: Backing-up is Behaviour.

A Task is a particular series of behaviours that must be performed by each element at any point in time. For example: When its bucket is full, a truck must move along a haulage road from a loading point to a dump point. When a truck arrives at a dump position, it must place itself to perform dumping; when a truck arrives at a loading position, it must place itself to allow the loader to fill its bucket. In order to accomplish each of these tasks, a wide variety of behaviours must be conducted: some in parallel and some in sequence.

Tasks are repetitive operations carried out in sequence by an Agent or group of Agents. Some Agents perform one, and only one, particular task over and over again as new "customers" arrive to be serviced. Other Agents conduct different tasks dependent on their interactions with other Agents and on the circumstances that change in the system (environmental, design, unexpected events, interruptions, etc.).

**Conclusion**

The field of automation is changing at a rapid pace. While at first glance; automation appears to devalue labor by replacing people with machines, in fact, automation leads to advancement in intellectual capacity and higher-skilled mine operators. Automation leads to an improved quality of life and better workspace for people, as risks and exposure to unsafe environments are minimized. Automation increase equipment utilization and efficiency.

For an AHS project to be successful, organizations must identify and analyze levels of interest, expectation, priorities and influence of stakeholders in the early stages, as well as develop a management plan which incorporates quality control, risk management, communication plans, and exit strategies. It is important to identify the Major Critical Success Factors (CSFs) related to an autonomous haulage truck project and develop a Balanced Scorecard (BSC) as a management framework to identify and monitor CSFs. Great effort should be given to performance measures, as they allow warning alarms, target performance, and time trend comparisons both within the organization and with others benchmarking quality records (Enterprise Performance Monitoring).
Performance Measure ensures the new technology is being evaluated with respect to relevant indicators that measure both positive and negative contributions of the automated process.

Simulation software can help organizations predict benchmarked KPIs as well as discover new KPIs to use in accommodating changes from new technology. This simulation tool can be used in any open pit operation designed to receive autonomous haulage technology. Each mine is unique; to this end, the autonomous truck behaviour will differ. By incorporating the levels of variables in each mine, this offline tool can assist project managers to optimize projects resulting in more assertive decision-making.

Acknowledgment

The authors wish to express their appreciation to BHP-Billiton Nickel West Division for the funding of this research and for access to important data and information regarding autonomous haulage systems.

References