INDUSTRY ANALYSIS OF AUTONOMOUS MINE HAUL TRUCK COMMERCIALIZATION

by

Scott Brundrett, P.Eng.
Bachelor of Applied Science, University of British Columbia, 2003

PROJECT SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF BUSINESS ADMINISTRATION

In the Management of Technology Program
of the
Faculty
of
Business Administration

SIMON FRASER UNIVERSITY

Summer 2014

Approval

Name:	**Scott Brundrett**
Degree:	**Master of Business Administration**
Title of Project:	**Analysis of Autonomous Haul Truck Commercialization**

Supervisory Committee:

Dr. Aidan R. Vining
Senior Supervisor

Dr. Pek-Hooi Soh
Associate Professor, Strategy / Technology and Operations Management

Date Approved:

Abstract

This analysis researches the commercialization of autonomous vehicle technology, specifically in surface mining operations. Autonomous technology refers to self-driving vehicles in particular mine haul trucks. It is an important topic because the global demand for minerals is increasing and mining is becoming more challenging. Mining companies seek to reduce costs and make operations safer, especially in developed countries with high labour costs.

Background on autonomous technology comes from research on the state of personal autonomous vehicles. A comparison between the requirements and conditions of automating personal automobiles versus mine haul trucks explains why autonomous haul trucks are available sooner. The analysis explains how haul truck manufacturers are entering the market by vertically integrating supporting technology and trialling the equipment at various mines. An economic analysis of the savings due to autonomous haul trucks helps explain where they are showing up in the market place and the magnitude of benefits to being a market leader.

To understand how players compete in this market, this analysis describes the advantages of being an early entrant versus a late follower. It considers customer lock-in and network effects. There is speculation on the strategies that late followers could take to compete with early entrants and whether there would be a standards war. Finally, the analysis predicts how brand leaders will maintain market share and take actions to be prepared for when it shrinks.

Table of Contents

List of Figures

List of Tables

1: Introduction

This analysis explores how autonomous mine haul truck technology will become commercialized in the near future. Its purpose is to assist equipment manufacturers and mining companies with decisions about how to develop and implement the technology.

1.1 Autonomous Vehicle Technology

Autonomous mine haul trucks are also known as driverless or robot haul trucks. To be fully autonomous a robot must have the ability to gather information about its environment. It must also be able to perform tasks while it moves around in its environment for extended durations without human assistance.

In fields such as space exploration, fully autonomous robots do the tasks that are too dangerous for humans in such an inhospitable environment. They are also desirable for freeing people up from performing routine chores such as vacuuming or mowing the lawn.

One way to think of autonomous machines is that they have the highest level of automation. Merriam-Webster Dictionary defines automation as replacing human labour by controlling an apparatus, process or system with mechanical and/or electrical devices (Merriam-Webster Dictionary 2014). There are various levels of automation in automobiles. Anti-lock braking and stability control are features that have been available in personal vehicles for a long time. Now many cars have sensors that indicate when your vehicle is too close to an obstacle during parking and can even stop the car from moving to prevent an accident. In the US, the National Highway Traffic Safety Administration (NHTSA) has established a classification system that identifies five levels of automation. It starts with level zero where the driver completely controls the vehicle at all times. It goes to level four where the vehicle performs all safety-critical functions for an entire trip with the driver not expected to control the vehicle at any time, which could include unoccupied cars.

Most people have a car or have often been a passenger in one, so it is easier to relate to how autonomous technology works in a personal vehicle, rather than a mine haul truck. In August 2012, Google announced that their self-driving car had completed over 300,000 autonomous driving miles accident free. Although four states have passed laws permitting autonomous cars, the cars must still have a driver ready to take control of the car at any moment. The Google car has about $150,000 of equipment to navigate the vehicle, which includes a $70,000 laser radar sensor. This sensor can detect objects such as other vehicles. This laser radar can also make three- dimensional maps of its environment. Another component of the self-driving car is Global Positioning Systems (GPS), consisting of satellites in space and sensors on vehicles, which assist in navigation by measuring and calculating a vehicles location.

There are many benefits of self-driving vehicles on public roads, but there are also many challenges to overcome. A few main potential benefits include fewer traffic collisions, relief from the chore of driving and navigating, and removing the constraint of a vehicles occupant's state. For example of the latter, it would not matter if the occupants were blind, distracted or intoxicated. Some challenges to commercializing this technology include liability for damage, communication security, determining the severity of road hazards, a loss of driver-related jobs, and the resistance of drivers to give up control of their car. Self-driving haul trucks in mines share some of the same benefits and challenges of self-driving vehicles on public roads. However, they also have their own benefits and challenges. Subsequently, autonomous mine haul trucks will likely be adopted at a faster rate than consumer vehicles, which becomes apparent when the two applications are compared.

1.2 Projection of Autonomous Technology in Personal Vehicles

The concept of autonomous cars has been around since the mid-19th century with the introduction of cars guided and controlled by wires. It was not until the 1980's and 1990's when cars followed the path of the roadway using lasers and sensors. Currently, many of the major auto manufacturers are developing and testing self-driving cars. While fully autonomous vehicles are not commercially available, many cars do have cameras and radars that support much more automation including adaptive cruise control, lane-keeping control, collision avoidance, and parking assistance. These car manufacturers estimate that they will be selling cars that drive themselves for at least part of the time by 2020. Forecasts indicate that by around the 2030s fully autonomous vehicles will be available. At that point, there will be 10 – 100 million autonomous vehicle sales annually in the United States.

1.3 Importance of Autonomous Vehicle Technology to Mining

The application of autonomous technology to haul trucks in mining has been receiving a lot of attention recently due to increase in mineral demand, lower availability of skilled workers, and mineral deposits that are lower grade and in more remote locations. The global demand for minerals and metals has seen record increases. For example, consumption of copper, one of the most widely used metals, has approximately doubled in the last twenty years. Increase in copper demand is mostly from growing countries such as China (Geology.com 2014). The result of a decade long boom in the iron ore business in Australia has reduced the availability of qualified mine haul drivers and increased their average annual salary to over $100,000. As conveniently located mines are depleted, new mines are now often located in remote areas where it is difficult to attract workers. There are also significant costs to fly them in and out of the mine site and cater to them while they are there. Autonomous haul trucks have the potential to improve performance, reduce costs and improve safety to overcome these challenges in mining.

1.4 Benefits of Autonomous Haul Trucks to Mining

Mine haul trucks are very large expensive machines that usually operate 24 hours a day. Without drivers, utilization of expensive equipment increases since it does not have to sit idle during lunch breaks or between shifts meaning that each truck. Therefore, fewer autonomous trucks carry out the same amount of work as manually operated trucks. Automated trucks also save cost because they operate more efficiently including shorter cycle times, lower fuel consumption, and improved tire wear. Furthermore, human safety improves simply by having fewer personnel in a dangerous mining environment. While this technology eliminates some jobs at a potential cost savings, it also creates new ones with improved worker skills in safer workspaces.

1.5 Economic Analysis of Autonomous Haul Trucks

Findings indicate that there is significant positive economic potential to implementing autonomous haul trucks in mines. Three major areas where it reduces costs are improved productivity, reduced labour and lower investment costs (Accenture 2010). One thesis study of actual autonomous haul truck data showed that haul truck productivity increases by about 21% due to increased utilization. Therefore seven autonomous mine haul trucks could replace nine human operated mine haul trucks. Fuel consumption is improved by about 6% and tire wear improved by over 7.5%. The results from this study of using autonomous haul trucks indicate a 49% after tax internal rate of return including labour savings (Parreira 2013). Large mines in developed countries where there are higher wages are primary candidates for autonomous haul trucks from a cost savings perspective.

1.6 Autonomous Haul Truck Manufacturers and Users

Autonomous haul truck technology is being tried and tested by various manufacturers and mining companies. The three main haul truck manufacturers that are pursuing the technology include Komatsu, Caterpillar, and Hitachi. They have each collaborated with mining companies (including Rio Tinto, BHP and Fortescue) to implement their technology in real mine operating environments. The majority of these systems are in in the Pilbara region of Western Australia where mining of enormous amounts of iron ore occurs. It started there in 2008 for Komastu with Rio Tinto and in 2011 for Caterpillar with BHP. Hitachi's first implementation of autonomous haul trucks was in 2013 at a Coal Mine operated by Stanwell. Suncor just introduced an autonomous haul truck by Caterpillar in the oil sands of Alberta.

1.7 Haul Truck Technology Development Strategy

The navigation for autonomous mine haul trucks is supported by the manufacturer's fleet management system. Fleet management systems have been around for about thirty years. They consist of software applications and hardware products that improve mining operations productivity, safety, and equipment availability. For example, a fleet management system optimizes haul truck assignments to reduce queuing time at loading and dumping stations. More recently, fleet management systems have expanded to include controlling autonomous haul trucks.

The core competency of haul truck manufacturers has been in the production of large industrial vehicles rather than databases, communication networks and sensors, which are the backbone of fleet management systems. As a result, fleet-management systems have typically been developed by independent companies and generally purchased by the equipment manufacturer overtime. Those haul truck manufacturers with the most advanced fleet-management systems have also been the first movers in autonomous haul truck technology.

Haul truck management systems are not able to control another manufacturer's trucks because they are each developing their systems independently. It is acceptable that there is no connectivity standard for vehicles in an autonomous mining environment because there are no pubic vehicles. The fleet management system controlling the autonomous haul trucks can still detect the other manufacturer's vehicles operated by people and cause the autonomous vehicles to take appropriate action, such as stopping and waiting until the manned vehicles have cleared the zone. However, no more than one brand of autonomous vehicles will be able to operate at the same mine site until there is a common connectivity standard.

Car manufacturers are collaborating with each other to develop technology that supports autonomous vehicles, opposite to the approach of early entrants' autonomous haul truck manufacturers. On public roadways, one vehicle cannot control another and make it stop, for example. Therefore, it is more advantageous for car manufacturers to work together on a connectivity standard. This is happening with Ford, General Motors

(GM) and Toyota among other industry partners collaborating to build a “simulated urban environment” for testing connected and automated cars (Thurlow 2014). There is also the Open Automotive Alliance (OAA) conceived this year, which is a global alliance of technology and auto industry leaders such as Google, Audi, GM, Honda, Hyundai and others. They intend to bring the Android platform to vehicles and allow automakers to more easily bring cutting-edge technology to their drivers (Open Automotive Alliance 2014). One connectivity standard will eventually prevail in the automotive industry and it could transfer to the mining industry as a better option than those developed by individual mine equipment manufacturers working independently.

1.8 Diffusion of Autonomous Haul Truck Technology

Autonomous haul truck technology is still in its infancy stage. Early entrants have the advantage of gaining experience and can become more efficient in subsequent technology development. There are a limited number of mines where it is practical to introduce the technology. The early entrant manufacturers will get those locations, pre-empting them from late followers. A company recognized as the leading brand of autonomous haul trucks because of their early entrance will have a preferential advantage over followers when new customers are evaluating which manufacturer to select.

On the other hand, the technology is expensive to develop and late followers could spend less on development failures. Fast followers can take advantage of advanced supplier technology and improve their product before offering it to the market. They get to learn from the mistakes of the early entrants, with less financial cost and failure risk. They have time to evaluate the wants and needs of the customers that are now educated about the product and provide a potentially better and differentiated product (Palumbo

2014). While early entrants could become brand leaders, a standards war is unlikely as open source platforms allow competitors to develop less costly and more effective technology.

1.9 Achieving Increased Market Share and Returns

For the leading manufacturer(s) of autonomous mine haul trucks the prize can be increased market share and increased returns. Each haul truck costs millions of dollars and a mine could have anywhere from less than seven to more than fifty trucks working in its mine pit(s). If a mine enters into a trial with one manufacturer, that manufacturer has a greater chance of selling a whole fleet of haul trucks to that mine over another manufacturer. They will also have the advantage of selling that mine other future autonomous equipment such as expensive shovels that load the haul trucks. When a mining company wants to expand autonomous haul trucks to another one of its mine sites, the same manufacturer will again have the advantage because of brand specific training, and databases, among other things.

1.10 Followers Strategy

Late followers that want to enter the autonomous haul truck market need a strategy to compete with the early entrants. This analysis considers a couple of options that late followers could be considering. Followers that have a stronghold in a specific geographic region could quickly trial their autonomous technology there. Then that follower could catch up to early entrants and compete in other markets. Other followers could focus on developing autonomous haul trucks compatible with open source platforms to provide less costly and more flexible products.

The overarching challenge of implementing autonomous haul trucks is that it requires a huge change in managing operations, human skill sets and technology integration (Accenture 2010). For such an enormous change to be successful, it must be implemented incrementally (Meech 2012). It will take time for a mining company to integrate autonomous haul trucks and other equipment into a mining operation and further into its business operation and business model. Therefore, it is important to develop a strategy for integrating autonomous haul trucks into a mining company's operations so its employees can adapt effectively.

1.11 Structure of Analysis

The analysis starts in chapter 2 and 3 by introducing and reviewing autonomous vehicle technology in consumer automobiles. This provides some background to the focus of this analysis, which is the application and commercialization of autonomous haul trucks in the mining industry.

The first item discussed about autonomous haul trucks in chapter 4 is its importance and benefits to the mining industry. Chapter 5 analyses the economics of autonomous haul trucks including estimates of savings depending on various sizes and location of mines, related to varying labour costs. Chapter 6 outlines the current state of the technology and introduces the equipment manufacturers and mining companies involved in autonomous haul trucks.

Chapter 7 explains how manufacturers vertically integrated fleet management systems into their organization. It predicts that manufacturers who have not integrated fleet management systems already will avoid it and work with several independent providers based on open source systems. Chapter 8 outlines the advantages of being an early entrant and conversely the advantages of being a late follower in the technology development. Chapter 9 considers how a firm can increase their market share with customer lock-in and network effects. Chapter 10 discusses strategies that followers could take. The analysis concludes in Chapter 11 explaining how early entrants with leading brands could gain more market share and maintain their overall growth in light of more competition.

2: Review of General Autonomous Vehicle Technology

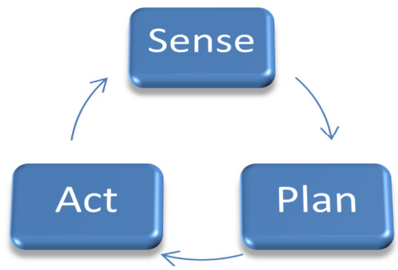
2.1 What is Autonomous Driving?

Autonomous vehicles have the ability to drive from one location to another without guidance or assistance from a person. They do this by collecting data about their environment, understanding the data and taking appropriate actions. A variety of sensors collects data. On-board computers process the data and instruct the steering, accelerating and braking operations. Autonomous vehicles also transfer data between other vehicles and infrastructure, such as stop signals. There are varying levels of vehicle automation leading to full autonomy. Automobiles will go through each level before they can routinely operate autonomously. While this section provides the background on self–driving automobiles, there are many different applications for autonomous vehicles besides public transportation. Many work vehicles can be autonomous including mine haul trucks, which is the focus of this analysis in further sections.

2.1.1 Underlying Technology

The basis for robotic systems design is sense-plan-act. First, an autonomous vehicle must understand its environment. Autonomous vehicles use a set of sensors to gather information. The autonomous vehicle processes the collected information to determine what action to take. Finally, the cycle is completed and then it starts again, as shown in Figure 1.

Figure 1: Foundation of Robotic Systems: Sense-Plan-Act



2.1.2 Sensors

The main sensors found on autonomous vehicles include light detection and ranging (Lidar) systems, radio detection and ranging (Radar) systems, and visual cameras. Each sensor provides different types of information and has its own limitations, so a set of various sensors or arranged around the car collect depending on the type of information they collect. Lidar systems are the most prominently featured sensors on autonomous vehicles. They measure distance by emitting laser lights toward a point and analysing the reflected light. Lidar systems can emit multiple lasers. When combined with rapidly rotating mirrors they can generate three-dimensional models of their environment. The two main limitations of a Lidar are its useful distance (up to about 140 metres) and that certain materials do not reflect the light back well. While Google paid 140,000 dollars for one system, reports indicate that the price of this equipment could soon drop drastically making it only a small fraction of the vehicle cost. Radar sensors also detect the distance of objects in this case by emitting radio waves; they are much less expensive than Lidar sensors. They are good for detecting metallic objects, but do not detect pedestrians well, for example. Examples of other low cost sensors are ultrasonic and infrared. Ultrasonic sensors accurately detect close range objects and are useful for parking. Infrared sensors are useful for detecting pedestrians and cyclists, even in the dark.

Camera based systems, like the human eye, can collect a lot of very rich information at great distances. However, algorithms for camera-based systems cannot interpret visual data with the same level of sophistication as the human eye. Changing environmental conditions make interpretation even more challenging for cameras. Therefore, it is necessary to have a suite of sensors, which serves two purposes. First, locating them at different locations around a vehicle can overcome the limitations of each individual type of sensor. Second, integrating sensors with each other can provide a greater perception than the sum of the individual sensors (Anderson, Kalra and Stanley 2014).

2.1.3 Navigation Systems

On-board Global Positioning Systems (GPS) estimate the location of a vehicle in relation to a road map by receiving signals from orbiting satellites. While this is very useful for allowing an autonomous vehicle to choose the most direct route from one location to another, it has its limitations. The accuracy of GPS in determining a vehicle's position can vary by meters even under ideal conditions. This error increases when objects block or cloud signals, such as skyscrapers on a city street or mountains and valleys in the country. Inertial navigation systems (INS) reduce the vehicle positioning error when the GPS signal is lost. INS includes on-board sensors, such as accelerometers and gyroscopes that continuously calculate and update the location of the vehicle without external information. However, after 10 seconds without GPS signals, even the most sophisticated INS could have a position error of about a meter (Waze 2014).

More sensors and systems on a vehicles offer more capabilities, but they also add to the complexity and cost of autonomous vehicles. Given the limitations of sensors and accuracy of positioning systems, for example, it is clear that improvements in technology are required before automobiles will be fully autonomous (Anderson, Kalra and Stanley 2014). However, automobiles will have increasing automation technology on-board as they progress towards full autonomy.

2.1.4 Levels of Autonomy

In 2013, the National Highway Traffic Safety Administration (NHTSA) released a policy on automated vehicle development. Its purpose is to provide guidance to individual states permitting and testing emerging vehicle technology, in particular for safety. The NHTSA outlined five levels of automation, reproduced in Table 1 below. They define that autonomous or self-driving vehicles operate “without direct driver input to control steering, acceleration, and braking and are designed so that the driver is not expected to constantly monitor the roadway while operating in self driving mode” (NHTSA 2013). The NHTSA suggest that technologies lending to autonomous vehicles have the potential to significantly reduce thousands of fatalities and injuries each year as well as reduce fuel consumption. They recognize that vehicle sensors described in previous sections do not only guide vehicles, but also more importantly are crash avoidance systems. As technology development evolves, vehicles progress through levels of autonomy that will come with increasing benefits to safety and relieving demand on drivers.

Table 1: Official Autonomous Vehicle Classification System Established by National Highway Traffic Safety Administration (NHTSA), United States

No-Automation (Level 0):	The driver is in complete and sole control of the primary vehicle controls – brake, steering, throttle, and motive power – at all times.
Function-specific Automation (Level 1):	Automation at this level involves one or more specific control functions. Examples include electronic stability control or pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone.
Combined Function Automation (Level 2):	This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centring.
Limited Self-Driving Automation (Level 3):	Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The Google car is an example of limited self-driving automation.
Full Self-Driving Automation (Level 4):	The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

The NHTSA is currently very involved in level one automation technology research. Their work centres on developing test procedures and assessing the safety benefits of this first level of technology. They have started planning level two and level three automation research. Two main components include driver-vehicle interaction and electronic control safety. They want to ensure that drivers safely transition between automated driving and manual driving modes. They want to make sure electronic control systems are safe from a reliability point of view and cyber security perspective. They expect their work on developing standards for these areas to take three to four years. They suggest that vehicle-to-vehicle (V2V) technology could be an important component to self-driving vehicles so that they have more awareness of their surroundings. NHTSA's policy reinforces that automation technology will be implemented incrementally in vehicles before eventually leading to full self-driving vehicles.

2.2 Key Benefits

Autonomous vehicles have the potential to reduce accidents, reduce transportation costs and relieve people from the chore of navigating and driving.

2.2.1 Safety

The rate of roadway fatalities has decreased from 50 to 10 fatalities per billion vehicle miles travelled over the last fifty years (Anderson, Kalra and Stanley 2014). However, there were still 32,000 deaths related to automobiles in the United States during 2011. Many factors have contributed to the reduction in fatalities including on-board safety systems such as airbags, anti-lock brakes, electronic stability, and most recently collision warning systems (CWS). Some of these technologies also contribute to automotive automation. It takes many years for these technologies to migrate from a small percentage of luxury vehicles to the majority of vehicles because for example, it takes time to replace old cars. As more automation safety systems become mainstream, the rate of fatalities will continue to decrease and the level of autonomy in vehicles will increase. Estimates indicate that distracted drivers cause thirty percent of accidents, which has only recently surpassed drinking and driving as the number one cause of accidents (CBC News Canada 2013). Autonomous technology can prevent accidents related to driving under the influence or distraction.

2.2.2 Other Benefits of Self-Driving Vehicles

Beyond making roads safer, autonomous vehicles have many other benefits. However, improvements to human safety is by far the most compelling reason to invest in the development of autonomous vehicle technology for consumer automobiles. Autonomous vehicles make driverless taxis available, which could have lower fares. They also relieve the headache and cost of parking in urban centres with automated valet. While relieving individuals from the chore of driving could allow people to spend their time in vehicles doing something more productive, it is difficult to place a value on it. However, providing self-driving cars to individuals with driving limitations, such as the visually impaired, is invaluable. There are many more benefits of self-driving personal vehicles.

2.3 Key Challenges to Overcome

While there are costs to self-driving vehicles, experts agree that the above benefits outweigh the costs. Ironically, some of the costs are consequences of the benefits. For example, autonomous vehicles could disrupt parking business and valet jobs since nearby parking may not be necessary. Many driver occupations would be lost as well, such as truck drivers and taxi drivers. Fewer accidents are likely to reduce the amount of work for auto body shops, too. Though more work needs to be done to estimate these costs, the overwhelming benefits indicate that it is prudent to overcome the challenges of implementing autonomous vehicles on our roads. Some of the challenges to resolve for the safe and manageable deployment of self-driving cars include:

- Policies regarding liability for damage
- Resistance of individuals to forfeit control of their cars at higher costs
- Software reliability and cyber security
- Implementation of Legal Framework and Government Regulations
- Loss of Driver-Related Jobs
- Reliance on Surface Markings for Staying in Lanes and determination of traffic obstacles and traffic intensity

3: Future of Autonomous Vehicle Technology

Sensor technology has advanced significantly over the past decades. However, there are many challenges of deploying this autonomous technology, the largest of which is reliable perception of the environment around the vehicle. Many stakeholders believe that sensors alone will always be too expensive and will never provide enough reliability. It is suggested that telematics will play an increasing role in autonomous vehicles. Telematics refers to the transfer of information to and from vehicles and road side infrastructure, known as Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I), respectively.

3.1 Dedicated Short-Range Communications

There are many platforms for communication between vehicles such as cellular networks (3G and 4G), Wi-Fi and Bluetooth. Governments are also supporting dedicated short-range communications (DSRC) by dedicating bandwidth of the electromagnetic spectrum for V2V and V2I. This provides much more advanced data to vehicles about their surroundings compared to sensors alone.

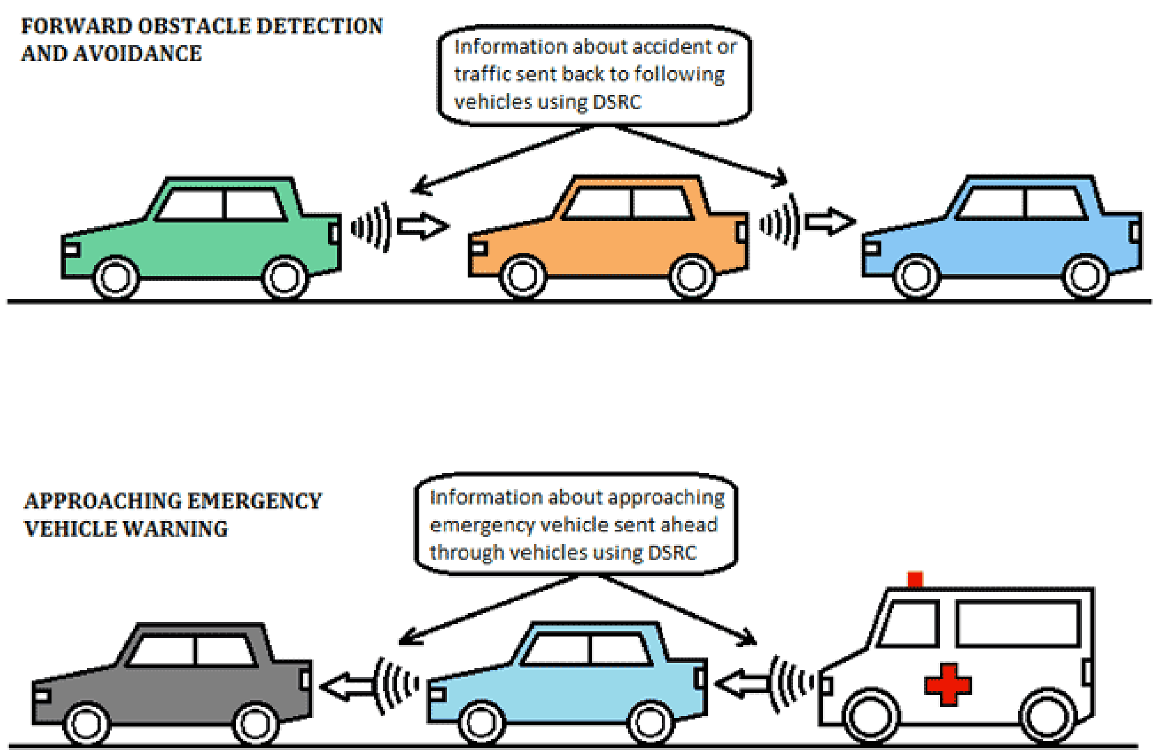
3.2 Mapping

The problem with maps today for autonomous vehicles is that they are static and do not provide the most up to date information, such as construction or debris in the roadway. Google recently purchased a community map developer called Waze. Waze maps get updated information about activities on the roads from members in its community, such as accidents so that other members know to avoid those areas. Expectations are Google will integrate the Waze technology into their autonomous vehicles (Waze 2014). The key advantage of this technology is that when one vehicles' sensors detect a change in the road environment, it instantly notifies all the other vehicles around it. Technology such as Waze, can overcome outdated maps, by continuously updating them with information provided in real time by vehicle sensors.

3.3 Forward Obstacle Detection

DSRC has the ability to provide advanced warning of potential objects ahead by sending signals backwards to notify drivers of obstacles up to about 1000 meters away as shown in Figure 2. Likewise, information about approaching emergency vehicles comes from further back vehicles indicating to safely move out of the way and clear the road (Clemson University Vehicular Electronics Laboratory 2014).

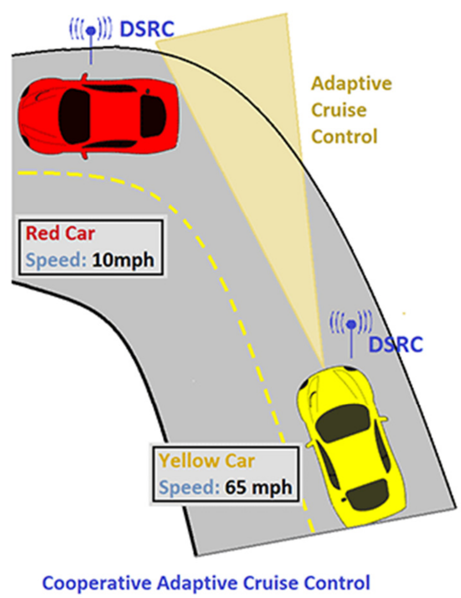
Figure 2: Uses of Dedicated Short Range Communications



Source: Clemson University Vehicular Electronics Laboratory (CVEL)

Dedicated Short Range Communications (DSRC) supports other applications in addition to forward obstacle detection and avoidance. For example, as shown in Figure 3, cooperative adaptive cruise control is useful when normal adaptive cruise control cannot detect a slow moving vehicle that is up ahead on a sharp curve. Even if it is out of the line of sight from the vehicles radar or Lidar scanner, cooperative adaptive cruise control can warn the vehicle that it will have to slow down even before the Lidar or Radar sensors detect the vehicle. Or if a bike or a pedestrian is equipped with a DSRC enabled smartphone, the vehicle can be alerted to their proximity and avoid a potential accident.

Figure 3: Cooperative Adaptive Cruise Control



Source: Clemson University Vehicular Electronics Laboratory (CVEL)

3.4 Technology Forecast

The expectations from many important stakeholders is that vehicle connectivity is necessary to promote autonomous vehicles on public roadways. The US Department of Transport envisions a wireless communication system that connects cars, buses, traffic signals, cell phones and other devices. This will require a large amount of infrastructure and a critical mass of vehicles to be equipped with the technology. It will take time to add the technology to enough vehicles or to replace old vehicles with new ones that have the technology on-board. Furthermore, these vehicles will have to communicate across the same platform (i.e. DSRC, Bluetooth, or cellular). Since some car manufacturers are already using different platforms, this could slow down the acceptance of a single platform. For example, two Ford vehicles rely on drivers using their smartphones to link to their network, while GM is providing connectivity in its new vehicles with 4G LTE. Although, it seems complicated to connect so many different personal and commercial vehicles on public roads, it is not so complex to do in a mine, with mining vehicles.

It is much easier to implement autonomous vehicles at a mine site compared to the public roadways because at a mine site one entity is responsible for all the vehicles. On public roadways, individuals are responsible for their own cars and decide where they want to go and how they will get there. In a mine, the mining company generally owns and operates all the vehicles on the site. At least, the mining company has some sort of authority over all vehicles. Therefore, it is much easier to control the interaction of vehicles in a mining environment when it comes to autonomy. The mine could physically separate autonomous vehicles from non-autonomous vehicles. Alternatively, they could outfit all vehicles on site with radio-frequency identification (RFID) tags. RFID tags communicate the proximity and position of many things including vehicles. With RFID tags, if a non-autonomous vehicle gets too close to an autonomous vehicle, the autonomous vehicles stop and wait until the non-autonomous has cleared the zone. Being able to provide connectivity between vehicles and having the authority to decide which vehicles have the right of way, means that deploying autonomous vehicles in a mine environment is much less complex than on public roadways.

4: The Importance of Autonomous Haul Trucks to Mining

4.1 The Role of Haul Trucks

Mine haul trucks are off-highway dump trucks designed and built for high production mining. The capacity of these trucks is ever increasing to reduce the operating costs at mines. First introduced in 1998, Caterpillar's current third-generation model 797F has one of the largest payload capacities in the world, up to 400 short tons or 363 metric tonnes. The job of these trucks is to haul waste rock and mineral ore from open pits as shown in Figure 4. Large shovels load the trucks. They haul waste rock up and out of the pit along ramps to a dump area. That exposes the valuable mineral ore, which they then haul from the bottom of the pit to a processing plant for milling and concentrating.

Figure 4: Open Mining Pit, Haul Trucks and Shovels

Haul trucks have one of the biggest jobs at a mine. New mines have throughputs of hundreds of thousands of tonnes per day. For example, the Cerro Verde copper mine in Peru is currently undergoing an expansion to increase its ore throughput from 120,000 metric tonnes per day (mtd) to 360,000 mtd (Freeport-McMoRan Copper and Gold 2014). If one truck hauls approximately 360 tonnes per trip, then their fleet of haul trucks must make about 1000 trips per day. There are currently over 38,000 haul trucks with capacity over 90-ton payload operating around the world (Mining Magazine 2013).

4.2 Challenges in Mining

Demand for mineral resources has increased significantly over the past few decades. Mineral resources demand will continue to grow strongly especially from developing countries, in particular in Asia. As these countries industrialize, more and more people will migrate from rural areas to urban centres. They will improve their standard of living by continuing to construct more buildings, power and communication networks, and personal vehicles all of which require minerals and metals. While this is good news for countries that are large suppliers of minerals such as Australia, Canada, and Russia, they also must maintain their competitiveness. There are many challenges facing mining companies including declining quality and accessibility of mineral deposits, a shortage of skilled workers, and increasing demands for safety of workers (Fisher and Schnittger 2012).

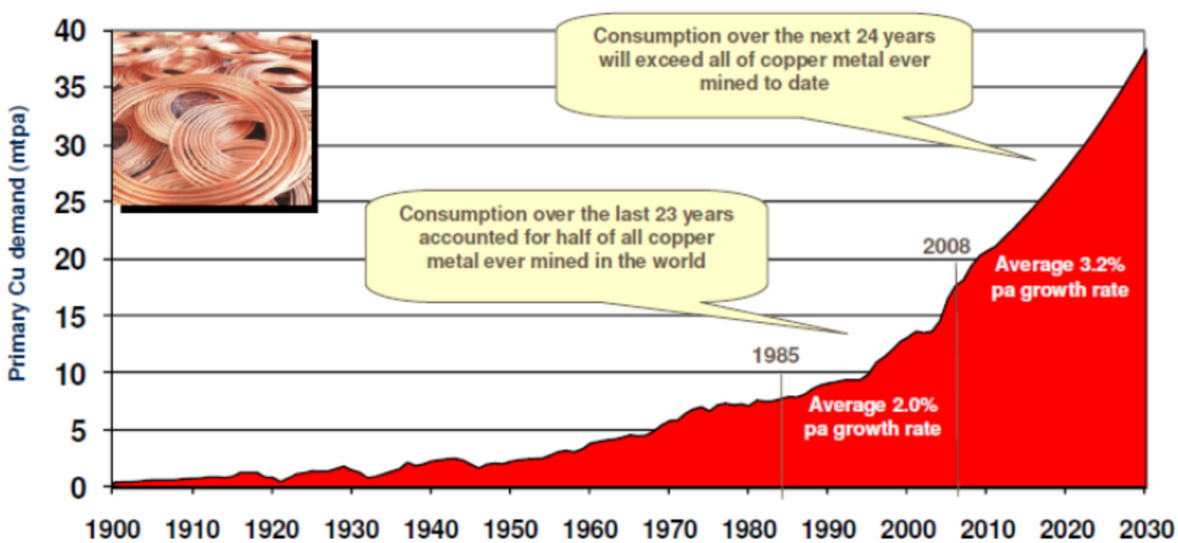
4.2.1 Increasing Demand for Minerals

The Organization for Economic Co-operation and Development (OECD) forecasts that the world economy will grow on average at 3% per year for the next 50 years (OECD 2012). That means it will double by the year 2030 and nearly triple by 2050. The growth of non-OECD countries will continue to outpace OECD countries although the gap will narrow over time. Expectations are that non-OECD growth rate will decrease from over 7% per year, during the last decade, to 5% by the 2020s. By 2050, non-OECD will drop to half of that, while OECD growth will average about 2% per year.

While the standard of living in emerging countries will continue to be much lower than developed nations, their income per capita will increase 4 – 7 times by 2060 (Fisher and Schnittger 2012). Continued economic growth will increase the demand for minerals.

The result of migration from rural to urban areas and a rise in the standard of living in developing countries means increased construction of housing, buildings, power and communications infrastructure, and personal automobiles. Copper, a base metal, is a very good example of a material used in all these applications. **Error! Reference source not found.** shows that between 1985 and 2008, the consumption of copper accounted for half of all the copper ever mined in the world. It also indicates that the consumption of copper during the 24 years between 2008 and 2030 will exceed all copper metal ever mined (Fisher and Schnittger 2012). The demand for copper and similar base metals such as zinc and nickel continues to increase.

Figure 5 World Primary Copper Demand

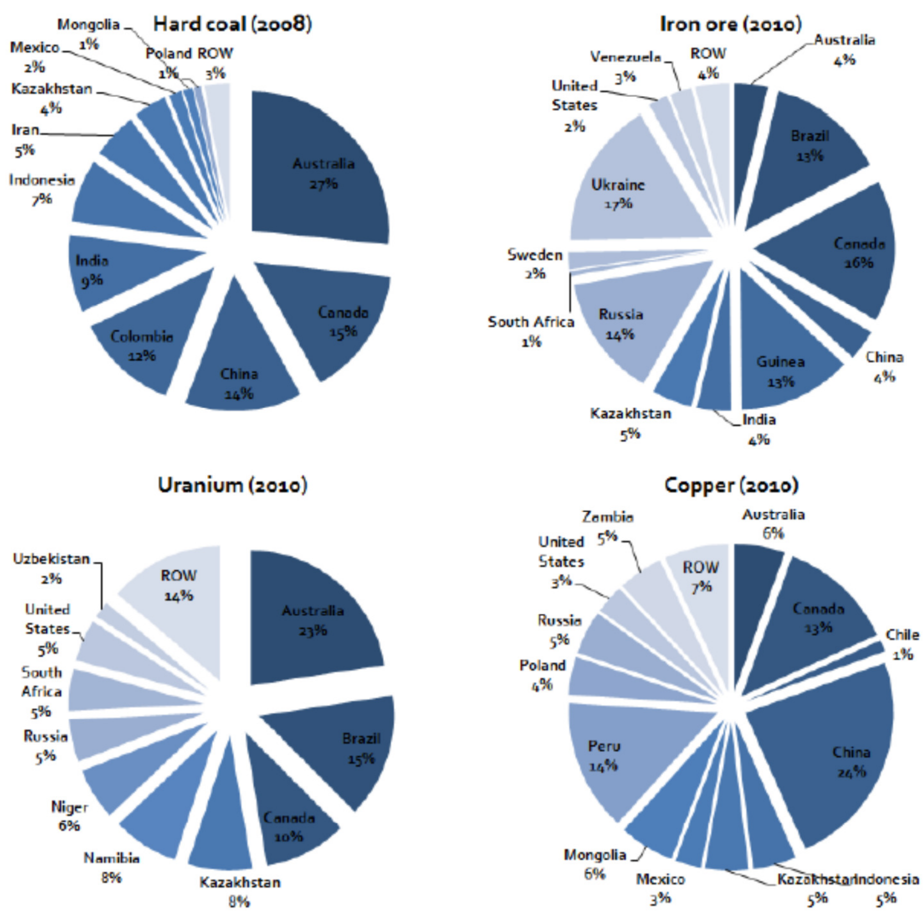


Source: Fisher, B. and Schnittger, S, 2012 *Autonomous and Remote Operation Technologies in the Mining Industry: Benefits and* Cost, Figure 2-5, pp. 13

4.2.2 Increasing Competition from Developing Countries

Emerging countries are becoming the main consumers of mineral products for their industrialization and development. Some of them are also the largest holders of mineral resources. China is the largest producer of iron ore at 1,320 million tonnes in 2013, followed by Australia at 530 million tonnes and Brazil at nearly 400 million tonnes. Although Brazil is the third largest producer, its reserves are much higher than the two largest producers, which are Australia and China, each with 4% as shown Figure 6.

Figure 6 Percentage of World Reserves for Selected Commodities by Country



Source: Fisher, B. and Schnittger, S, 2012 *Autonomous and Remote Operation Technologies in the Mining Industry: Benefits and* Cost, Figure 2-2, pp. 8

While the governments of some developed countries have provided infrastructure to support the development and export of natural resources, mining operations need to increase efficiencies. For example, Australia competes with Brazil to be the largest seaborne trader of iron ore. Furthermore, recent announcements of major iron ore developments in New Guinea indicate increased competition amongst producers (Fisher and Schnittger 2012). While the infrastructure to get iron ore on to their ships is a significant component of the overall economics of their operations, they also have to consider the cost of labour to mine, haul and load this ore onto ships including associated tasks. The cost of labour between Australia and Brazil (and other developing countries) can be drastically different and is an important part of their marginal costs.

There are more reasons why mining operations in developed countries have to improve the efficiency of their operations to be competitive with emerging countries. This is especially true for minerals that require more processing than iron ore, like copper and other base metals for example. Developed countries generally have safety standards and environmental regulations that require greater upfront investment and ongoing expense. Increasing demands to improve the health and safety of workers in mines and to reduce the impact on the environment means these mining operations need to invest in their operations and efficiency.

4.2.3 Lower Grade, Less Accessible Deposits

Remaining mineral deposits are becoming more costly to mine. Mining of high-grade mineral reserves closest to the surface and existing infrastructure happens first. What is left after these most attractive deposits are depleted are ones that are typically lower grade, deeper and in more remote locations. Figure 7 shows how the head grade of copper ore has declined by over 30% from 1.5% to 1.0% copper in ore, since the 1990's.

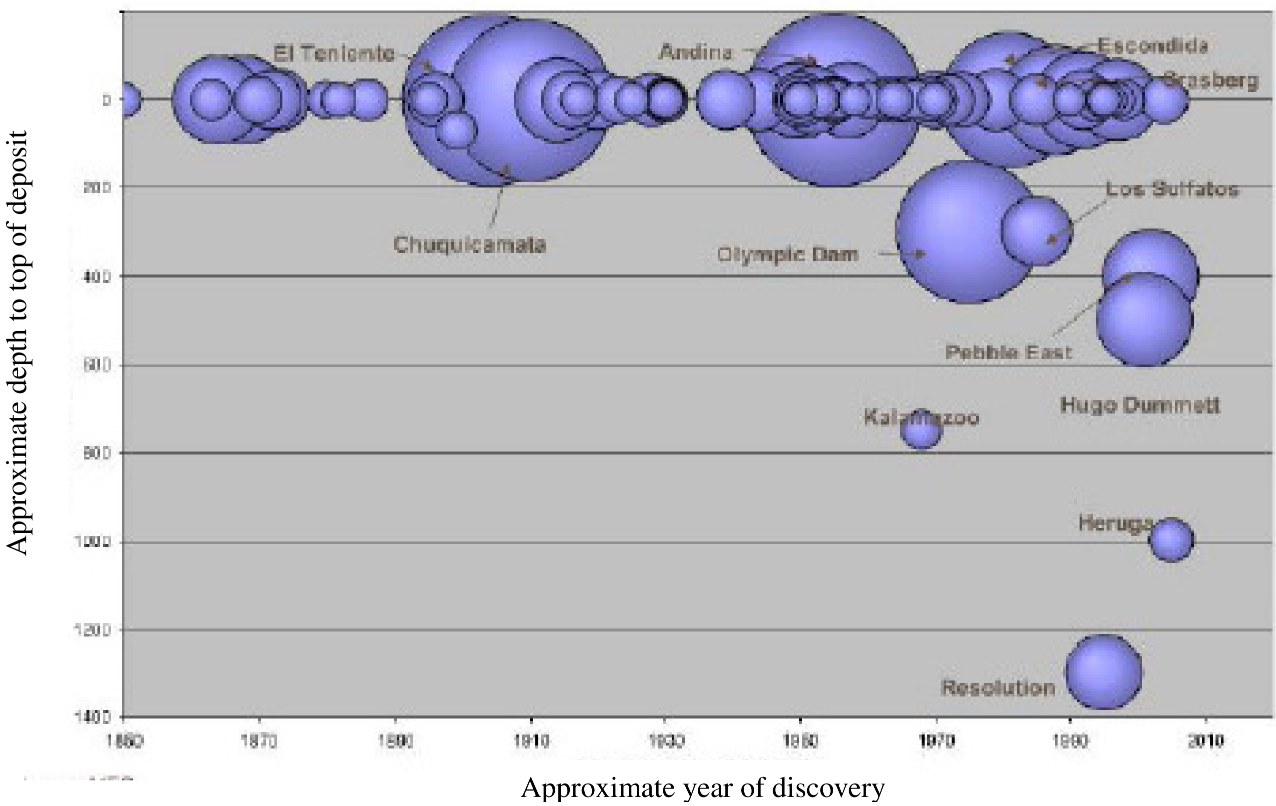
Figure 7: Average Feed Grades of Copper

Source: Fisher, B. and Schnittger, S, 2012 *Autonomous and Remote Operation Technologies in the Mining Industry: Benefits and* Cost, Figure 2-7, pp. 15

Head grade is the percentage of the metal in the ore before it is concentrated at a mill and sent on for further purification processes such as smelting and refining. In order to produce the same amount of copper from a 1.0% grade ore compared to 1.5% grade ore, it is necessary to mine 50% more ore. One of the largest costs of mining and processing more ore is transporting it from the pit to the milling facility where it is concentrated.

Figure 8 shows that the more recent copper deposits discovered are deeper from the surface than previous discoveries (Fisher and Schnittger 2012). The deeper the deposit from the earth's surface, the more development required to access it. To mine a large low-grade deposit by open pit methods could mean that millions of tonnes of waste rock need to blasted and hauled out of the way to another location. Only then is the valuable ore beneath it available to remove and process. As new deposits are lower in grade and further from the surface, more and more hauling of material is required.

Figure 8: Copper Discoveries Showing Depth of Deposits with Greater than 4 Mt Contained Copper



Source: Fisher, B. and Schnittger, S, 2012 *Autonomous and Remote Operation Technologies in the Mining Industry: Benefits and* Cost, Figure 2-8, pp. 15

4.2.4 Shortage of Skilled Workers

Increasing demand for minerals has led to a shortage of skilled workers around the world in the mining industry. While new mines are technically advanced, they are also often located in remote areas. Hiring highly skilled workers can be challenging because these jobs often require flying in and out of the mine, being away from family and working in a less than pristine environment. If miners are not able to fill positions requiring skilled workers, they cannot efficiently increase their production and remain competitive. In order to attract skilled employees, from other industries for example, mining companies need to pay higher wages. They also need to invest more in training of their semi-skilled workers and of course focus on labour saving technologies.

4.2.5 Improved Worker Safety and Environmental Impact Requirements

Mining is one of the most dangerous occupations and considered a very dirty industry. There are so many dangers at a mining operation. One example is the open mining pits. Falling rocks, slope failures, blasting rocks and the interaction between humans and gigantic trucks pose serious threats. The unintended operation of moving vehicles, such as haul trucks, is a leading cause of accidents. Limited visibility and blind spots due to the size of the vehicles and operator fatigue or complacency are just two examples.

Mining is energy intensive and produces large quantities of waste among other environmental concerns. Nations are calling for all industries to reduce their carbon intensity emissions, and mining is no exception. Mining operations in developed countries need to find practical and cost effective ways to reduce their environmental impact to compete on a global market against mines in emerging countries that often have less stringent environmental requirements.

4.3 The Benefits of Autonomous Haul Trucks to Mining

Haul trucks, such as the robotic versions pictured in Figure 9 carry ore from the mine to the processing plant. Ore blasted from in the pit is loaded into the haul trucks with larger shovels or loaders. Typically, they drive a few kilometres and dump the ore at mill where it is ground to smaller sizes and often concentrated before moving onto further processing. The following benefits of autonomous haul trucks, including improved safety, utilization, and performance, and lower labour costs provide answers to the challenges described above.

Figure 9: Robot Trucks Fitted with Radars, Lasers and GPS Systems

4.3.1 Safety

Autonomous haul trucks improve safety primarily by simply removing humans from the dangerous mining environment. Additional sensors and improved communication systems required to navigate autonomous haul trucks, improve safety by detecting objects such as workers. Trucks operate more safely because there is no risk of fatigue or complacency no matter how long the vehicle operates.

4.3.2 Equipment Utilization

Autonomous haul trucks have higher utilization rates because they do not have to stop for lunch breaks or switching drivers, which represents a significant amount of downtime for each machine. As a result, fewer autonomous haul trucks are required compared to manual haul trucks to move the same amount of material.

4.3.3 Improved Performance

Autonomous haul trucks outperform manually driven haul trucks because they operate more consistently. They travel between locations along the most direct path every time without swaying. Human operators can take longer to drive between locations especially as they get later into the shift. Autonomous vehicles break, accelerate and shift gears more efficiently. They do not site idle due to driver change over or other similar stoppages. This all adds up to reduced fuel consumption, less tire wear, fewer equipment failures, and faster cycle times (Parreira 2013).

4.3.4 Reduced Labour and Related Costs

Eliminating drivers from haul trucks represent the greatest cost savings of autonomous haul trucks. There are less chartered flights or other special transportation requirements. With less drivers on site, there is also less support staff required, especially in remote locations where catering is required. Subsequently, there are less investment costs in operations camps, since less people work on the site. The labour savings from automating trucks is much higher than the additional labour to run the autonomous trucks.

The additional labour to run autonomous haul trucks includes system managers and more instrumentation technicians. While haul truck drivers are eliminated, autonomous haul truck systems must still be monitored and managed. It requires different skills because these managers are looking after several vehicles rather than driving one. However, many of these employees can work from centres located in urban areas and interact with the autonomous vehicles via Ethernet. The addition of high tech sensors and computers on board autonomous haul trucks requires highly skilled instrumentation technicians.

5: Financial Analysis of Autonomous Haul Trucks

There is limited costs and savings data available for autonomous mine haul trucks. Haul truck manufacturers do not publish this type of information. Even financial data for existing operations of manually driven haul trucks is very limited. In this chapter, performance data of autonomous haul trucks versus manually driven haul trucks comes from a recent PhD thesis by Parreira, 2013 based on data from an operating mine. Cost data comes from various sources including Parreira. The extrapolation of performance data to various mining scales combined with salaries of operators in various economic regions provides a rough order of magnitude savings for different mining scenarios. This analysis is only an indication of the potential savings since information is limited.

5.1 Fewer Autonomous Trucks Needed for the Same Hauling

In the mine studied by Parreira, autonomous haul trucks travel a shorter distance than manually driven trucks to haul the same amount of material because operators drive to parking lots for their lunch, breaks and shift changes. This adds about 16% more distance in one shift and adds one hour of travel time per 12-hour shift (Parreira 2013) compared to autonomous haul trucks. Therefore, in one day, there are two hours of unproductive driving time. This could vary based on the distance to the parking lot and whether drivers go there for their breaks and shift changes.

Autonomous trucks are also utilized more than manually driven trucks. Manually driven trucks stop for about one hour while drivers take their meal and other breaks each 12-hour shift. Between shifts, the truck rests for up to another hour during driver turnover. Therefore, in one day each truck sits idle for three hours. Between sitting idle and driving longer distances, manually driven trucks are 5 hours less productive than autonomous trucks per day. While many other factors influence the productivity of manually driven truck vs. autonomous truck, breaks and shift changes are the biggest factors. They make manually driven trucks around 20% less productive. As a result, approximately seven autonomous haul trucks can move the same amount of waste rock and ore as nine manually driven haul trucks each day at the studied mine (Parreira 2013).

5.2 Increased Cost of Autonomous Haul Trucks

The capital cost of haul trucks is significant. The trucks at the mine studied are Cat793D, which have a payload capacity of 225 metric tonnes. The estimated capital cost is $4 million each. The estimated capital cost of the equivalent autonomous haul truck is $5 million. The additional cost for each autonomous vehicle is not available from multiple sources. It could change as the technology develops. For example, it could decrease as sensors and other components become more readily available. However, equipment suppliers are also likely to demand more of the value proposition that autonomous haul trucks provide mining companies. Nonetheless, based on the above figures, nine manually driven haul trucks cost $36 million and seven autonomous haul trucks cost $35 million (Parreira 2013).

Autonomous haul trucks require additional costs for system set-up including telecommunications and positioning infrastructure, design, installation, training and commissioning. For the example system of seven autonomous haul trucks, the assumed cost is nearly $7 million as shown in Table 2. However, not all set-up costs are directly proportional to the quantity of haul trucks in the system. Larger fleets of autonomous haul trucks have economies of scale advantage since some elements such as monitoring systems will not increase as much as other elements.

Table 2: Autonomous Haul Truck Infrastructure Cost Assumptions

Element	Quantity	Unit Cost	Total
Infrastructure Telecom / IT			
Basic transmission station	30	$30,000	$900,000
Servers (with redundancy)	8	$12,500	$100,000
Routers	10	$40,000	$400,000
Switches	20	$5,000	$100,000
Energy System (with redundancy)	1	$150,000	$150,000
Network Adaptation (Cables CAT 6)	1	$200,000	$200,000
Monitoring System (Camera, SW specific, etc)	1	$1,500,000	$1,500,000
Positioning System with redundancy (DGPS, antennas, etc.)	1	$200,000	$200,000
Subtotal			**$3,550,000**
Services			
Installation and Commissioning	1	$700,000	$700,000
Consulting (12 months)	4	$180,000	$720,000
Project Manager (6 months)	2	$100,000	$200,000
Transmission Link	2	$10,000	$20,000
Training	20	$50,000	$1,000,000
Transport/logistics	1	$500,000	$500,000
Subtotal			**$3,140,000**
Total			**$6,690,000**

Source: (Parreira 2013)

5.3 Reduced Fuel Consumption

There are a few main reasons why autonomous haul trucks consume less fuel than manually driven haul trucks. Autonomous vehicles drive more consistently with less or no side-to-side swaying which reduces their travel distance. They also change gears, accelerate and brake more efficiently, and they do not waste fuel driving to the break or shift change area. It was determined that autonomous haul trucks have about 5% - 7% better fuel consumption than manually driven haul trucks for the case where 7 autonomous haul trucks replace 9 manually driven trucks. Based on the reported fuel consumptions (Parreira 2013) and other assumptions shown in Table 3, there is an estimated annual fuel savings of about $1 million when 7 autonomous haul trucks replace nine manually driven trucks at a mine production of about 38,000 tonnes per day.

Table 3: Fuel Consumption Savings

	Manual Trucks	Autonomous Trucks	Units
Mine production	37,867		tonnes of ore per day
Fuel consumption	0.83	0.76	litres of fuel per tonne of ore
	31,430	28,779	litres of fuel per day
	11,471,808	10,504,306	litres of fuel per year
Fuel cost	$1.00		USD per litre
	$11,471,808	$10,504,306	USD per year
Annual fuel savings	**$967,502**		**USD per year**

Source: Author

5.4 Reduced Tire Wear

Autonomous haul trucks have lower tire costs because of reduced tire wear. Each haul truck has six tires at an approximated cost of $33,000 each, or nearly $200,000 per truck. On average, manual haul trucks have a tire wear rate at 0.015 mm/cycle, while autonomous haul trucks have a tire wear rate of 0.014 mm/cycle or a reduction of 7%. Typical tire life averages about 5,500 hours of operation at an average speed of 20 kph. At a 65% utilization rate and with proper care they are useful for about 100,000 km and need replacement in about 13 months (Parreira 2013). Therefore, over a seven year period a fleet of manual haul trucks needs about 300 replacement tires at a total cost of $9.9 million. A 7% improvement in tire wear is equal to a savings of $0.7 million in real dollars when replacing a fleet of nine manual haul trucks over their assumed 7-year life. While the savings on tire wear does not significantly contribute to the additional autonomous haul truck capital cost, it does make a positive contribution.

5.5 Operator Labour Savings at Different Pay and Production Scales

The operator labour savings from autonomous mine haul trucks can vary widely from one operation to the next depending on driver wages and the mining rate. Driver wages vary significantly from some countries to others. Mine operations have various quantities of mine haul trucks depending on the deposit and the size of the trucks. Reducing the number of operators at remote mining operations that require operators to fly in and fly out of the site provide additional savings. This section estimates the range of savings by substituting autonomous mine haul trucks at various sizes of mines with various pay scales.

The mining production rate will vary from mine to mine depending on the size and grade of the deposit. Mines that require a large infrastructure investment often require a minimum operation for several years or more. There are many factors that go in to determining the mine life, including limitations of equipment mining rates, amortization of equipment costs and volatility in commodity prices. Large, low-grade deposits require many more haul trucks compared to small, high-grade deposits.

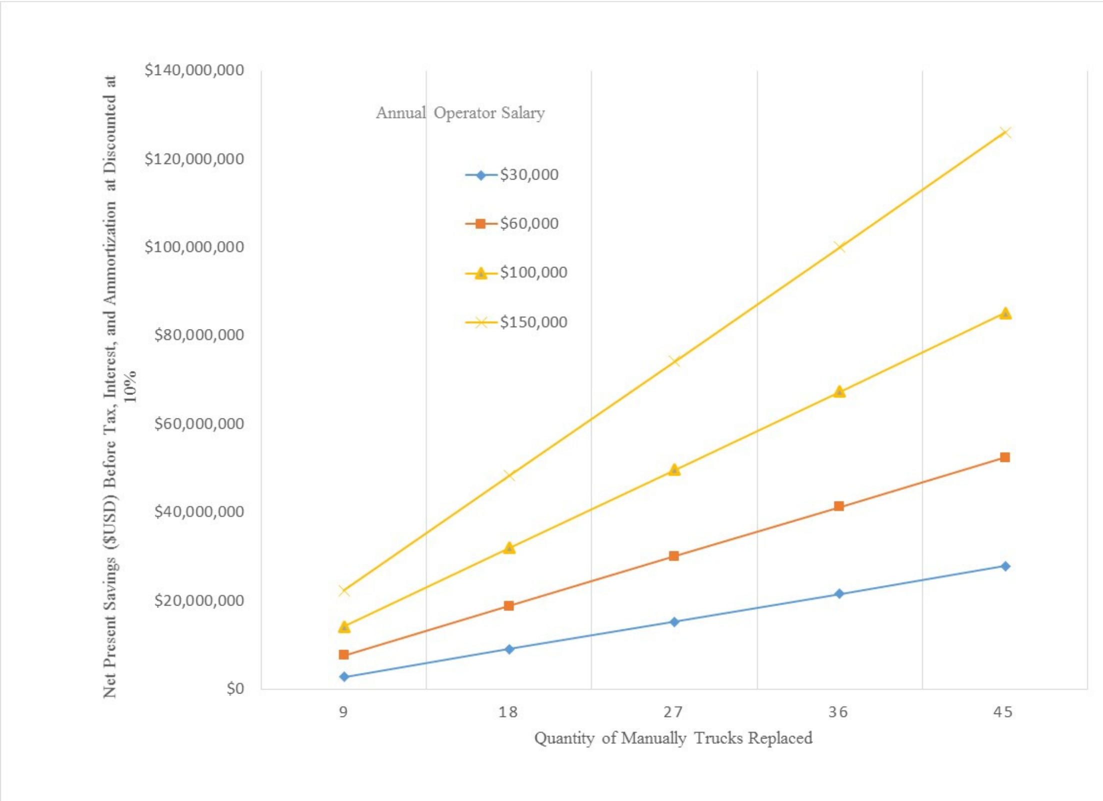
The quantity of mine haul trucks is specific to every mining operation. Suncor’s oil sands in Alberta, has a fleet of 67 Caterpillar mine haul trucks, of which 51 are 797s and 16 are 793s models. In 2008, there were 120 of the 797 haul trucks operating in Alberta oil sands with plans at that time to increase it by 65 additional 797 trucks each with a capacity of 363 metric tonnes (Mining.com 2008). While Suncor does not mine minerals, the operation of getting oil sands to the fuel upgrading facility is very similar. Diavik, Canada's largest diamond mine in the Northwest Territories used 11 Komatsu 830E and 8 Komatsu HD785 haul trucks with capacities of 218 tonnes and 90 tonnes, respectively (Rio Tinto 2009). Rio Tinto's iron ore Yandi mine in the Pilbara region of Australia also has a similar number of haul trucks at 23. They have 10 Komatsu 730E and 13 Komatsu 830E, 190 tonne and 220 tonne capacity respectively. Rio Tinto and others have several different iron ore mines in the Pilbara. The quantity of haul trucks varies from one mine to another from less than 10 to over 50 and many more in some places.

Labour rates also vary significantly amongst economic regions, especially between developed countries and emerging countries. Reports of salaries for drivers in Australia's Pilbara region are as high as $250,000 per year, but are more often $130,000 to $150,000 per year similar to haul truck driver salaries in the oil sands of Canada (Penty 2013). In South America, mines such as the giant open pits at Antofagasta or Escondido in Chile have annual truck driver salaries at $60,000 to $70,000 per year (The Economist 2013). In the neighbouring country of Peru, where many new large mines are in development, mine haul truck driver salaries are about $30,000 per year and less. In many African and Asian nations where economies are less developed, salaries are even lower. Haul truck driver salaries vary greatly depending on the region.

Extrapolating the case of seven autonomous haul trucks replacing nine manually driven haul trucks provides a rough estimate of net present savings of employing autonomous haul trucks at various mine scales and pay rates, such as those described above. The main assumptions for the following extrapolation include staff levels, fuel savings, cost of autonomous haul trucks, and cost of supporting infrastructure and set-up. First, assume that it takes 4 people to operate each manual truck because each operator works a 12-hour shift, two weeks on and two weeks off. Vacations and absenteeism add 5% to the labour requirement bringing it to 4.2 full time equivalent (FTE) employees. Assume it takes 4.2 people at the same salary to monitor an autonomous haul truck system of seven trucks. Second, for each system of nine manually driven haul trucks replaced, there is a million dollars per year in fuel savings. Third, the cost difference between seven autonomous haul trucks and nine manually driven haul trucks is insignificant. Finally, for each additional set of seven autonomous haul trucks, the total infrastructure and set-up costs increase by 50% due to economies of scale. The calculation of the net present savings before tax, interest and amortization for all the scenarios considers a replacement life of 7 years and a discounted cash flow of 10%. Extrapolating the base case of replacing 9 haul trucks with 7 autonomous haul trucks up to an operation of 45 manually driven haul trucks using these assumptions provides only a rough estimate of the potential savings.

Figure 10 shows the potential for greater savings at large mine operations with high operator salaries compared to small mine operations with low operator salaries. At higher operator costs and a greater number of trucks the savings increase more compared to lower operator costs. When operators are earning $100,000 per year, replacing 45 manual haul trucks translates into a potential net present savings of roughly $80 million. Mines with the greatest quantity of haul trucks and the highest operator labour costs offer the greatest potential savings for autonomous haul trucks.

Figure 10: Range of Savings Varied by Quantity of Trucks Replaced and Operator Salary



Source: Author

6: The Status of Autonomous Haul Truck Technology

6.1 Equipment Manufacturers and Mining Companies

While the idea of autonomous haul trucks has been around since the 1970's, it is only within the past decade that the first ones appeared on mine sites. As shown in Table 4, Komatsu was the first to build and trial one in 2008. Caterpillar was not far behind with its first trial that started in 2011, followed by Hitachi in 2013.

These equipment manufacturers have teamed up with mining companies to trial their equipment. They work together to develop the technology. Haul truck manufacturers need a real mining environment to test the haul trucks and systems and achieve successful operating hours. Mining companies need the equipment manufacturers' specifically trained and experienced technicians to deploy and manage the operation during initial phases.

Table 4: Manufacturers of Autonomous Haul Trucks and the Mines Trialling Them

Equipment Manufacturer	Number of Trucks	Mining Company	Mine Site	Location	Trials Initiated
Komatsu	11	Codelco	Gabriela Mistral	Chile	2008
Komatsu	5	Rio Tinto	West Angelas	Australia	2008
Komatsu	10	Rio Tinto	Yandicoogina Mine	Australia	2013
Komatsu	5	Rio Tinto	Nammuldi	Australia	Future
Komatsu	19	Rio Tinto	Hope Downs	Australia	Future
Caterpillar	3	BHP	Navajo Mine	New Mexico	2011
Caterpillar	15	BHP	Jimblebar	Australia	Future
Caterpillar	45	Fortescue	Solomon	Australia	Future
Hitachi	3	Stanwell	Meandu	Queensland	2013

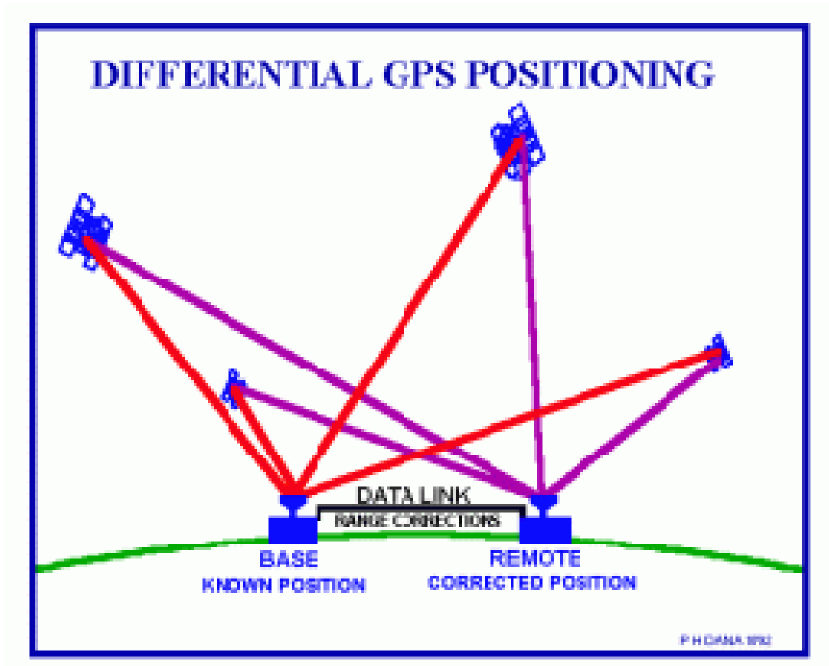
6.2 Projection of the Autonomous Haul Truck Market

The commercialization of autonomous mine haul trucks is happening faster than public automobiles. As described above, several mines have autonomous trucks in operation. Rio Tinto has committed to putting 150 autonomous haul trucks in operation at their mines by 2015. There are two main technical reasons why autonomous haul trucks are developing faster than autonomous public automobiles. First mines can install Differential GPS (DGPS) cost effectively, which significantly improves position identification accuracy. DGPS would be very costly for public automobiles. Secondly, fleet management systems provide vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connectivity. Vehicle connectivity amongst public vehicles and infrastructure is challenging because cars are manufactured by several companies and operated by independent owners in the same space.

6.2.1 Differential GPS

Differential correction improves GPS accuracies to within 1 – 5 meters, or even better when combined with advanced equipment. As shown in Figure 11, the accuracy of a mobile GPS receiver improves by using a second GPS receiver that collects data at stationary position. Geographical survey determines the location of the base station precisely. A calculated based on the location of the base station known provides any corrections to the mobile GPS. To communicate the correction factor between the base station and the mobile GPS requires a radio or other data link (GPS 2008). Many mines already have robust data communication systems to transfer data between vehicles and the control room. Improved GPS accuracy using differential correction makes autonomous navigation systems more practical.

Figure 11: Basic Differential GPS Diagram

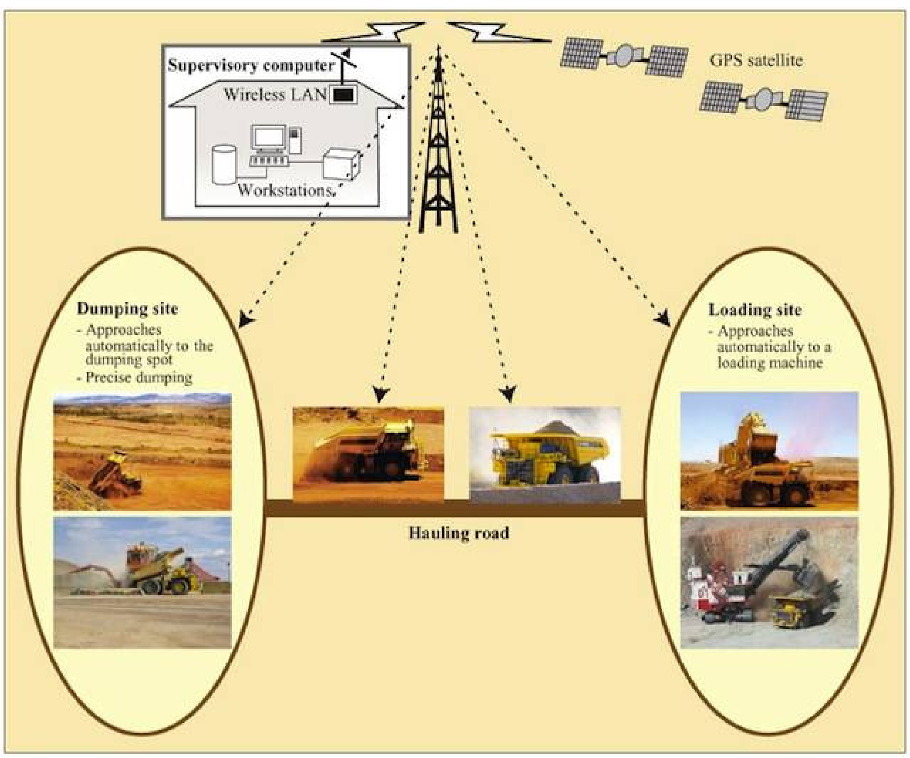


Differential GPS is practical for an open pit mine operation because the sites are finite in size and relatively small. Base stations and radio communications only need to have range around the pit and the usually nearby dump and parking locations. Therefore, the scope of the physical infrastructure is also limited. Conversely, installing GPS base stations on all public roads is a very large task. Given the financial reward, it is easy to understand why a mining company would invest in this type of infrastructure at their mine site, but more challenging to determine who would pay for a much larger scope of infrastructure on public roads.

6.2.2 Fleet Management Systems

Mine haul truck fleet management systems have the capability to connect with all vehicles at a mine site and communicate their locations to each other. The fleet management system used with Komatsu haul trucks has an element called RoadMap that continuously tracks the position of all vehicles. Fleet management systems also optimize haul truck assignments to reduce cueing times at loading and dumping stations, equipment health monitoring, and maintenance tracking as shown in Figure 12. Having all equipment connected to one system makes autonomous operation much safer. For example, when an autonomous haul truck and a light vehicle come into a defined proximity, the haul truck stops until the light vehicle has safely passed. Implementing a system that connects vehicles on public highways and roads will take much more time.

Figure 12: Autonomous Haul Truck Communication Systems



7: Technology Development Strategy

Modern fleet management has greatly evolved since development of the first systems in the 1980's. They are now an integral part of mine haul truck and other mining equipment operation. Basic fleet management is standard in most medium and large mines, while advanced features have helped leading mines maintain a position of lower cost and higher productivity. With the development of autonomous haul trucks, fleet management systems have become even more important. Due to its increased role in mining, there are more independent fleet management providers. Large mine haul truck manufacturers have also developed their own fleet management systems or purchased fleet management companies, specifically the haul truck manufacturers that offer autonomous systems including Komatsu, Caterpillar and Hitachi. Now, other haul truck manufacturers such as Liehber, XEMC and Belaz need to decide how they will approach fleet management and haul truck automation.

7.1 Broadening Haul Truck Manufacturer's Scope of Data Management by Acquisition

Seemingly, the three largest haul truck manufacturers are competing to ensure that they can each provide the latest features in fleet management so that miners buy their trucks. They want control over fleet management technology so that they can be leaders in autonomous haul trucks. As a result, Komatsu, Caterpillar and Hitachi have vertically integrated fleet management technology into their companies. Komatsu was the first manufacturer to integrate fleet management systems, followed by Caterpillar and most recently Hitachi.

In 1996, Komatsu purchased a majority share in Modular Mining systems and in 2003 acquired the outstanding shares to make it a wholly owned subsidiary of Komatsu. Conceived in 1979, Modula Mining was an early innovator in fleet management systems. At the beginning of the 1980's they developed the first mine management system that optimized haul truck assignments for dumping from pits. It improved productivity by 10%. Since then, they have been a leader in mine management technology, with systems operating in 8 languages and 200 customers since October 2010.

In 2000, shortly after Komatsu acquired a controlling interest in Modula Mine, Caterpillar introduced its own fleet management system called Minestar that they developed with their alliance partners. Then in 2004, 1 year after Komatsu purchased remaining ownership in Modular Mine, Cat announced MineStar 2 with performance improvements in several critical areas including machine-tracking system with safety protocols (Canadian Mining Journal 2004). Cat continues to improve MineStar applications and continues to add new features. Most recently, Caterpillar leveraged its fleet management technologies with the introduction of Cat Connect in 2014 that provides fleet management services to other industries that Cat services with its equipment, such as construction.

Given the competition between Caterpillar and Komatsu with fleet management systems and development of autonomous haul trucks, it is not surprising that Hitachi recently acquired a fleet management technology. In July 2009, Hitachi Construction Machinery Co. Ltd. announced that it was expanding its mining business and that it purchased Wenco International Mining Systems, Ltd. of Richmond, B.C. Wenco has 25 years of experience providing comprehensive fleet management systems similar to

Modular and Minestar. Now, as a subsidiary of Hitachi, Wenco purchased Automated Positioning Systems (APS) in April 2014. APS, founded in 2003, is proficient in independent machine guidance and navigation systems that support autonomous haul trucks. It follows Hitachi's announcement that they were beginning trials of three autonomous trucks at Stanwell's Meandu mine in April 2013. They additionally announced that they intend to offer a commercial autonomous haul truck solution by 2017. Buying a company specializing in navigation after they have already started their trial suggests that implementing an autonomous system is not straightforward and requires specific core competencies. Furthermore, the intention to provide an autonomous solution so quickly after their first trials suggests that they believe that being a leader in technology can gain them market share.

7.2 Future of Fleet Management Integration

Wenco suggested in a 2010 press release that they attribute the signing of their largest fleet management contract in part due to the open architecture philosophy of their system. This contract to monitor and control 40 shovels and 224 haul trucks at Coal India Limited's 4 mines required an industry standard ODBC compliant technology (Wenco 2010). ODBC refers to Open Database Connectivity, which is a programming language that allows applications to port to other platforms on the client and server side. Haul truck and other equipment manufacturers need to consider that they will have to offer compatible on-board management systems or relinquish opportunities to supply equipment for large contracts.

Haul truck manufacturers that have not already integrated a fleet management system into their company are likely evaluating whether it is worthwhile to do so in order to provide autonomous systems. If a manufacturer makes their autonomous haul trucks compatible with several fleet management systems, then mines who prefer those fleet management systems could also be preferential to the compatible brand of haul trucks. If a haul truck manufacturer purchases a fleet management system to integrate with their autonomous trucks, they may fail at making it superior or comparable to others. As a result, they could ruin their opportunity to sell autonomous or manual haul trucks. Being open to various fleet management providers, who compete amongst each other may result in a better fleet management system than the manufacturers who have one integrated fleet management solution.

Vertical integration is a means of coordinating the different stages of an industry chain. Fleet management systems are complementary products to mine haul trucks, which support their autonomy. Vertical integration is a risky strategy and when it fails, it can be costly to fix. Generally, it is not recommended to vertically integrate unless it is necessary to create or protect value (Stuckey and White 1993). Four common reasons to vertically integrate include high set-up costs, high transaction costs and risks, and challenges in coordination effectiveness as shown in Table 5 with examples of each.

Table 5: Primary Reasons to Vertically Integrate

	Setup costs	Transaction costs	Transaction risks	Coordination effectiveness
Examples	Capital (e.g. equipment acquisition)	Information collection and processing	Possibility of unreasonable price changes	Run lengths, inventory levels
	Systems development	Legal	Supply or outlet foreclosure	Capacity utilization
	Training	Sales and purchasing	Insulation from market (e.g., form technical changes, new products)	Delivery performance

Source: Stuckey and White, 1993

Due to the onset of open connectivity for autonomous vehicles in mining, haul truck equipment manufacturers must carefully consider whether to vertically integrate a fleet management provider into their company. As connectivity moves towards open platforms, development costs for autonomous truck management system become lower as they are not brand specific. Open connectivity platforms also reduce transaction risks and transaction costs since there are a variety of providers of these systems. Finally, open connectivity by its own virtue moves towards the elimination of coordination effectiveness problems. The probability that open connectivity for autonomous trucks and other mining vehicles is likely considering that open connectivity is the direction that autonomous public vehicles is moving towards.

7.3 Vehicle Connectivity Standardization

The future of automotive vehicle connectivity is now. Audi, GM, Google, Honda, Hyundai and NVIDIA founded the Open Automotive Alliance (OAA) in January 2014. It uses Googles Android operating platform to provide automobiles access to mobile services in a safe and seamless way. As shown in Table 6, the sheer volume of new members in the alliance announced in June 2014 only 6 months after inception indicates the shift towards an open platform for connectivity amongst public automobiles. The open platform concept or even this platform itself could migrate into the mining industry. It is important that mining companies and mining equipment manufacturers pay attention to developments of public automobile connectivity.

Table 6: Open Automotive Alliance Members

Automaker Partners

Abarth	Acura	Alfa Romero	Audi
Bentley	Chevrolet	Chrysler	Dodge
Fiat	Ford	Honda	Hyundai
Infiniti	Jeep	KIA	Maserati
Mazda	Mitsubishi	Nissan	Opel
Ram	Renault	Seat	Skoda
Subaru	Suzuki	Volkswagen	Volvo

Technology Partners

Alpine	Clarion	Cloud Car	Delphi
Freescale	Fujitsu Ten	Google	Harman
JVC Kenwood	LG	Nvidia	Panasonic
Parrot	Pioneer	Renesas	Symphony Teleca

An open environment for developing applications that connect vehicles to mobile devices is a Segway to V2V and V2I connectivity that supports autonomy of vehicles. The Open Automotive Alliance says, “by working with automakers to deliver [mobile service] experiences in ways that make sense for the automobile, drivers can get what they are looking for without disrupting their focus on the road (Open Automotive Alliance 2014)." A single open platform benefits application developers and hence automakers and drivers. With over 1 billion Android users currently, developers are already familiar with this platform. Therefore, instead of considering a variety of platforms from different automakers, developers focus on delivering a powerful experience. While the overriding initial focus of the OAA involves connecting entertainment services to public automobiles such as music, the development of the Google car and their interest in the OAA indicates that this platform will ultimately support vehicle autonomy in the near future.

8: Diffusion of Autonomous Vehicle Technology in Mining

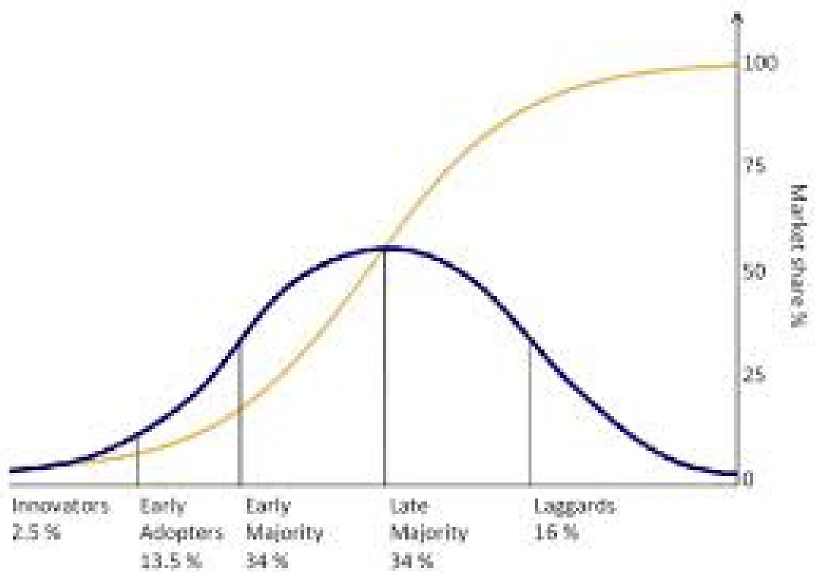
Diffusion of technology is the rate at which it spreads into the market. The diffusion of autonomous haul truck technology depends on both the strategy of mining companies and the equipment manufacturers. The following section evaluates them separately. This analysis refers to mining companies that have started using autonomous haul trucks as early adopters and late adopters. Manufacturers that have introduced autonomous haul trucks are early entrants, while those that have not are late followers. Each mining company and each equipment manufacturer have different strategies about the rate at which they pursue the technology depending on how they want to compete.

8.1 Stages and Rates of Adoption

The rate at which mining companies are prepared to adopt autonomous haul technology influences the effort that equipment manufactures will put into it. Autonomous haul trucks are in the early adoption stage by mining companies. Figure 13 shows generic stages of technology adoption and corresponding up take in market share. Autonomous haul trucks at mine operations are in the trial phase. While the status of how well trials are progressing is not publicly available, representatives of various haul truck companies indicated at tradeshows that there is a driver at the wheel to take control as necessary. This is similar to how the Google car trials operate on public roads in certain states in America. During the trial phase, equipment manufacturers are learning the features that mining company customers prefer.

There are a limited number of mines willing to trial autonomous haul trucks. Only mines with an extremely long mine life are good candidates. The mine life has through the trial period, and the implementation pay-off period. For example, a mine with a life of 5 – 10 years would not be long enough because by the time the trial is finished and autonomous haul trucks are fully implemented the mine would be near the end of its life. It is a much lower return on investment compared to a mine with a longer mine life. This is also why the largest iron ore and coal mines in Australia and the oil sands in Canada with huge haul truck fleets and long mine lives are the locations of the first autonomous haul trucks.

Figure 13: Stages of Technology Adoption



8.2 The Early Entrants' Advantage

The cost is high for the equipment manufacturer(s) to first develop and implement autonomous haul truck technology. However, pioneering firms have the potential to secure a lasting competitive advantage. The early entrants' advantages come from three major areas:

- Technological leadership
- Pre-emption of assets
- Buyer switching costs

8.2.1 Technology Leadership – Experience Curve Effects

Experience curve effects, and research & development expertise and patents are two forms of technology leadership that provide competitive advantage to first movers. The more times a task has been performed, the less time is required to perform each subsequent task. For example, automated production technology and information technology introduce efficiencies when implemented as people learn how to use them more effectively. This is particularly important for autonomous haul trucks because it requires major operational change in an industry that does not change quickly. Integrating the technology into current operations has challenges. For a mining company it will be expensive to develop integration, support and service skills in-house (Accenture 2010). Most will depend on the equipment manufacturer's expertise to transition them from a manual haul truck environment to an autonomous haul truck environment. Therefore, mining companies will prefer an equipment manufacturer with the capability to implement the technology quickly and train the mining company to operate the system independently and effectively.

An early start allows the early entrants to develop their technology longer. In the case of autonomous haul trucks, they have the advantage of trialling their equipment at real customer locations. As a result, they learn directly the preferences of their customers so that they can efficiently integrate them into the product offering.

8.2.2 Pre-emption of Customer Trial Locations

Pre-emption of scarce assets is another advantage that early entrants have over their competitors. In other industries, this could mean being the first to get a prime retail location on a busy main street, the most talented employees or key suppliers. To be able to gain experience curve effects, equipment manufacturers need to implement and trial their autonomous haul trucks at real mines. Therefore, a competitive advantage that early entrants get is the best choice of trial locations where they can get the best implementation experience. As early entrants take up trial locations, it is more difficult for late followers to find a mine to trial their equipment and accelerate the development of their technology. Finding the right mine to trial autonomous haul trucks gives the early entrant manufacturer the advantage over later followers.

8.2.3 High Switching Costs

Switching costs are one of the greatest early entrants' advantage. Transaction costs, contractual switching costs and buyer choice under uncertainty all add to high switching costs. Once a customer engages with a supplier, it is unlikely they will switch to a different supplier. Mine haul trucks cost approximately $4 - $5 million dollars each and there are additional costs for supporting infrastructure and information system. Once a mine selects a fleet of one brand of haul trucks, it is more costly to change brands it even after the equipment needs replacement after a few to several years.

Even before a mine company moves from trials into a full fleet, it is unlikely that they would switch to another supplier. The uncertainty of how well a competitor's equipment supply will perform trumps some level of potential deficiencies in the performance of the existing supplier. Furthermore, when a mine enters into an agreement to trial equipment, there are likely contractual clauses that make it less attractive to switch to another supplier. For example, Rio Tinto only started with a handful of Komatsu's autonomous haul trucks before announcing that they would eventually purchase a fleet of 150 across their various operations.

8.2.4 Brand Association

Brand differentiates one seller's product from another. It can be a name, design, symbol or another distinguishing feature. Early on livestock branding differentiated one person's cattle from another. These days we recognize the 'apple with a bite out of it' as the mark of Apple's high quality computer and other products. A brand is a collection of feelings, perceptions, quality, image, delivered guarantee and global status (BrandMover 2009). In the mining industry that does not change quickly, being able to display that you are innovative supplier will draw a lot of positive attention to your company and product at tradeshows and sales calls.

Early entrants define the attributes that are perceived as important through the process of significant trialling. Customer's perceptions and preferences become associated with the brand and become difficult to change (Lieberman and Montgomery 1988).

8.3 Late Followers' Advantage

Being a late follower also has competitive advantages. In particular, they reduce the risk of wasting investment on a product that is unsuccessful, they have time to adjust their offering to better suit their customers and they can take advantage of advances in underlying technology that supports the product. To be successful as a follower requires competency in executing efficiently and careful analysis of when to enter the market. Understanding how fast or slow the technology and the market are developing contributes to an organizations odds of succeeding with the resources they possess.

8.3.1 Reduced Financial Risk and Failures

While early entrants attempt to mitigate upfront costs by conducting trials prior to marketing, they still face a considerable investment risk in trying to get product adopters. Meanwhile, rivals who have not entered the race, still have opportunity. They have the benefit of learning from the early entrants' in-market experiments. They can avoid similar mistakes and jump ahead with better solutions. However, they have to choose an entrance strategy that provides a competitive advantage. Two examples of how to avoid the risk of wasted upfront costs in autonomous haul truck technology and still gain market share as a late follower include using a regional strategy and using an open platform strategy.

A company that has a large market share in a particular geographic region could take advantage of their market share in that region to execute a late follower strategy. Waiting until early adopters have accepted the technology reduces the follower's financial risk of developing technology and market acceptance. China-based Xiangtan Electric Manufacturing Corporation (XEMC) is an example of mine equipment manufacturer that could potentially execute this strategy with autonomous haul trucks. While they currently do not claim to sell AHT, they did sell four 230 tonne *manual* haul trucks to one of Rio Tinto's operations in the Pilbara region of Australia in 2011. This is the same area where Rio Tinto has implemented Komatsu's autonomous vehicles. XEMC is a leading mine haul truck manufacturer in China, hence have major competitive advantage selling haul trucks in China. In 2011, XEMC also sold their first 300 tonne haul truck to an operation in Mongolia as well as many 220 tonne models (International Mining 2011). This represents a market where XEMC could have a better opportunity to trial an autonomous haul truck over an early entrant with previous trial accomplishments, like Komatsu. Rolling out a technology quickly in this market and gaining similar experience to early entrants could later make them just as or more competitive in other geographical markets where they are not the leaders, such as the Pilbara in Australia.

The early entrants in the autonomous haul truck supply used a closed fleet management platform for connecting and controlling them at a mine site. For example, Caterpillar's MineStar fleet management system only controls Cat haul trucks and Komatsu's Modular Mine System only controls Komatsu trucks, though they can collect on-line data from other equipment. This is natural since other mine vehicles by different manufacturers are not equipped to operate autonomously. However, these manufacturers also do not collaborate on developing autonomous technology with each other because they each want to be the leader. For a follower to compete, they need a different strategy. One example they could take is making their autonomous haul trucks compatible with various fleet management system (FMS) based on open-source architecture.

Autonomous haul trucks that operate on an open-source fleet management system could be more attractive to mining customers. Using an open-source fleet management system, miners could select from a variety of compatible autonomous haul trucks, and in the future, various shovels, loaders, graters, drills and dozers brands to make a completely autonomous site with machines provided by various manufacturers. A variety of companies (both OEM and independent firms) provides FMS to the mining industry. Independent FMS providers primarily focussed on machine guidance can be very effective on the corresponding specific needs of individual customers. Independent providers may be more responsive when it comes to customization. They also have a shorter 'time to market' and can react quicker and at a lower cost to specific customer needs compared to large OEM's (Mining Magazine 2014). By integrating their autonomous mine haul truck with several different independent fleet management providers, followers can create a larger potential market entry.

Using open-source platform is not a new concept for achieving market share. Samsung used the open source android technology for mobile phone platform to create an advantage that they use to compete against Apple's operating system that is only available for Apple products. Between November 2013 and February 2014, Apple's smartphone market share in the US declined from 41.3% to 41.2%, while Samsung's increased from 26% to 27% (Oleaga 2014). Furthermore, Google collaborated with 40 car manufacturers and technology companies in the Open Automotive Alliance to connect public automobiles to their smartphones and each other using the Android platform. While some fleet management providers develop open-source systems, the Open Automotive Alliance work could open the door for more fleet management providers.

8.3.2 Time to Adjust the Product Offering

A follower avoids locking in to a technology or business model that may prove unsuitable to the evolving market. Early movers may focus on the preferences of their biggest most profitable customers in their innovation efforts. In doing so, they create more elaborate and higher priced products. When new growth comes in from different business models or new customer categories, it may not be possible for early entrants to readily change their product offering due to inflexibility in their organization. Late followers able to execute swiftly can position themselves to target customers that early entrants cannot accommodate as easily.

There are examples of where late followers take over market share from early entrants because they are able to capitalize on the pace of technological change. Samsung has become one of the market leaders in mobile phones easily surpassing Motorola, who invented the cell phone in 1973, and Nokia and Ericsson who were fast followers. Samsung leveraged their leadership in display technology and subsequently were able to integrate new components quickly in early design stages. They took advantage of miscues by early entrant leaders and provided stylish units that were not otherwise available (Wunker 2012).

A later follower can take their time and use resources to identify a niche or variation of the technology innovation. By pursuing the niche aggressively they may become known as the dominant player for that particular market need (Wunker 2012).

8.3.3 Supplier Technology Advanced

Followers can wait for supplier technology to advance before providing an autonomous haul truck solution. In doing so, they save on their own technology development expenses and provide a lower cost and/or more flexible introductory product that meets the requirements of their customers. Followers may even innovate a similar, but disruptive technology resulting from advances in supplier technology, which early entrants ignore because it cannibalizes its own business.

There is a big opportunity for haul truck manufacturers to find lower cost technologies to support their automation with so much focus by the public automobile industry developing autonomous vehicles. For example, open connectivity technology under development by Google and partners, as discussed earlier, may be adapted and spawn more fleet management companies with newer and better systems. On-board sensors, such as Lidar, which measures the environment around autonomous vehicles, will come down in price. Followers that identify the optimum time to enter the market will save investment costs and be able to provide a competitive product without as much upfront spending as early entrants.

9: Achieving Increased Market Share and Increased Returns

There are several reasons for a manufacturer to offer autonomous haul trucks, no matter whether they are an early entrant or late follower. As identified previously, mine haul equipment is a high up-front cost, so once a mine company selects a brand, switching to another is unlikely. This section focusses on how a haul truck manufacturers increase their market share and sales by locking in their customer on their product brand and network effects.

9.1 Locking in the Mining Customer on Brand

For a mine to purchase a manufacturer's autonomous haul trucks, they require brand specific training and corresponding information and databases because they are specialized assets that operate within a semi-closed system. They will typically enter into long run contracts for technical support, maintenance and replacement parts. These factors lock a customer in to that manufacturer's product for a long time. Haul trucks operate around the clock and need replacement throughout the life of the mine. Since they are not all replaced at once, they are typically replaced with the same brand as the original fleet that was purchased at the start of operations.

Operating and maintenance training are specific to the brand of the haul truck, even though each brand look and function similarly. They are expensive to operate and repair so it is important to do it properly. The more efficient the operator, the greater the production achieved. Moreover, incorrect operation leads to increased wear and downtime, resulting in lower productivity and higher maintenance costs. When it comes to routine and other maintenance, the more familiar the technicians are with the brand of the equipment, the quicker they can get the haul truck back into the mine for production. It is preferred to have one brand of haul truck for this improved availability, productivity, and lower spare part inventory.

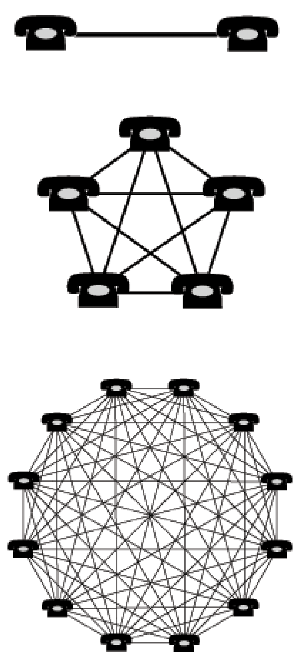
Special information and databases are unique to each haul truck manufacturer. This is especially true for autonomous operations because the information systems are more complex, with much more information transmitted and processed. It is more costly and complicated to have more than one brand of haul truck due to the investment in and management of information to operate and maintain the trucks. Current autonomous haul truck systems are only capable of controlling one brand of haul truck, the one that corresponds to the fleet management system of the manufacturer, such as MineStar to Caterpillar. Again, it obviously would not make sense to replace an autonomous Caterpillar haul truck that has reached the end of its life with an autonomous Komatsu haul truck because the systems do not interface. Databases, systems and even assets such as infrastructure that are all specific to one brand of haul truck create customer lock-in, which leads to the greater likelihood of future replacement sales.

Since haul trucks are such expensive and specialized pieces of equipment, customers agree to long-run contracts to guarantee the future price of services and parts. Equipment manufactures will often seek to negotiate such contracts with longer durations or special covenants that make it more worthwhile for customers to buy replacement trucks from them rather than their competitors. However, contractual obligations are probably a lower source of customer lock-in compared to the aforementioned brand specific training and systems. These reasons for customer lock-in on autonomous mine haul trucks contrast to one of high set-up costs and contractual pricing that may come up where one company builds a factory or infrastructure to provide a part or commodity to another company. In this case, brand specific training and system are less a source of customer lock-in, than they are for autonomous haul trucks.

9.2 Network Effects

In business, the network effect is a source of increasing returns. Network effects occur when one or more users of a good or service increases the value of that product to other users. Typically as number of users of the product increases, the more valuable the system is to all the users. The classic example is the telephone. As shown in Figure 14, the more people that own phones the more connections each person can make, which makes it more valuable to each person. This section identifies increasing market share for an equipment manufacturer from network effects at one mine site, and several mine sites of the same mining company.

Figure 14: The Network Effect in Telephone Systems



Generally, the more autonomous haul truck operations sold by one manufacturer the better for all those customers. With each new customer, the manufacturer has more revenue to invest in the development of the system that manages the haul truck automation. In a somewhat analogous example, the more iPhones sold by Apple the more applications developed for its operating system, iOS. Similarly, with autonomous haul trucks, a manufacturer with greater market share and returns will be more willing to invest in developing their fleet management software and other systems allowing that manufacturer to provide an ongoing better product to its customer base.

9.2.1 Compatibility within the Mine Site

Network effects at a single mine site lead a customer to purchase more of the same brand of autonomous haul truck. Just like brand specific training and brand specific systems lock-in customers on their original purchase, they also affect their brand choice when they expand their fleet. It is common for mines to find more deposits after mining starts at an initial deposit, such as the earlier example of Cerro Verde. As a result, they could purchase more haul trucks to increase their production. Therefore, when purchasing more autonomous haul trucks the customer will more likely purchase the same brand.

There are usually more haul trucks than any other piece of equipment at an open pit mining operation. However, there are many other pieces of equipment required for surface mining operation. Caterpillar is one manufacturer that has the capability to provide all this equipment as shown in Figure 15. Currently their fleet management system can monitor these pieces of equipment and provide the operator information to make them work more efficiently, but in the future, it will support their autonomy. This includes articulated trucks, hydraulic excavators, track drills, blasthole drills, motor graders, wheel dozers, hydraulic shovels and electric rope shovels. Mines with a fleet of autonomous haul trucks will be more likely to purchase that manufacturer's brand of other pieces of mining equipment when they become available in autonomous versions.

Figure 15: Caterpillar MineStar System Mining Equipment

Source: Caterpillar

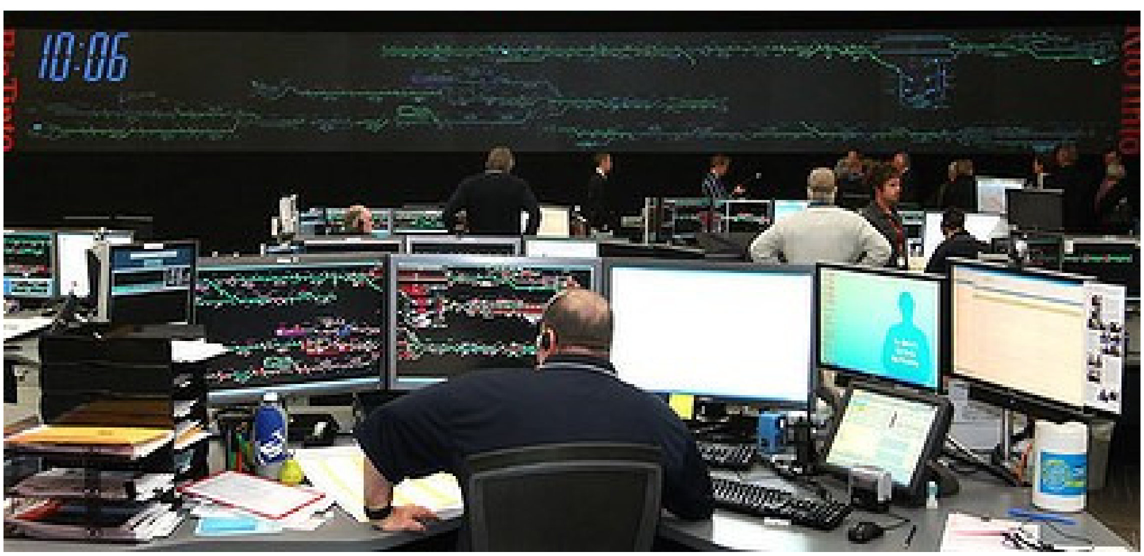
9.2.2 Connectivity between Mine Sites and Central Operations

Mining companies often seek to centralize as many of their operations as possible. Mines are often remote and it is challenging to get talented employees to work in these environments, compared to a major city. It is also expensive to have employees at mines because they demand higher wages and require transportation and accommodations.

Furthermore, many managers prefer central operations for closer control and greater visibility of the numerous activities they oversee. Therefore, the more mines that a mining company implements with a single brand of autonomous equipment, the greater the likelihood they will continue to use that same brand. It simplifies their control centre and makes operations more efficient compared to having more than one brand (Katz and Shapiro 1994).

Rio Tinto an early adopter of autonomous haul trucks is an excellent example of how the network effect can take sales of equipment from one mine to mines across their operations. As pictured in Figure 16, they implemented a control centre in Perth designed to monitor autonomous haul trucks, train and port operations throughout the Pilbara region of Australia. As these systems prove effective, and they learn how to operate them, they are likely to use the same autonomous equipment manufacturer when they expand automation to other mines.

Figure 16: Rio Tinto Operations Centre at Perth Airport



Source: Mogens Johansen,The West Australian

10: Followers' Strategy

This analysis has identified several factors for haul truck equipment manufacturers and mining companies to consider when deciding to pursue autonomous technology. The section provides an analysis of how late follower equipment manufacturers could attempt to enter the autonomous haul truck market. It also discusses some of the strategies that mining companies also late to adopt the technology could take.

10.1 Haul Truck Manufacturers

A fleet management system is an integral part of the autonomous haul truck operation. Through acquisition, development or a combination of both, early entrants have a designated fleet management system for their autonomous trucks. One path that a follower could take is an open-source fleet management strategy. The development of open source platform in the public automobile industry for instance, could transfer to mining fleet management systems. As a result, several independent fleet management companies could develop and supply the required navigation and corresponding technology just as or more effectively than existing haul truck manufacturers.

The other approach a follower could take is to start integrating and selling the same safety sensors that will likely be required for future autonomous operation, such as forward obstacle detection, adaptive cruise control and so on. Mining companies place safety as paramount importance for their operations, so they should be interested in these features. The equipment manufacturer taking this follower strategy can pay the cost to learn about this equipment with the revenue that it generates from selling them. Incorporating and selling safety sensors on mine haul trucks, like those becoming available in personal vehicles, develops their internal capabilities related to autonomous haul trucks.

10.2 Mining Companies

Mining companies considering a late adopter strategy for implementing autonomous haul trucks at their mine must be aware that the transition will happen slowly. To catch up and remain competitive against early adopter mining companies that transition to fully autonomous haul trucks first will be challenging. The late adopter that executes change quickly and efficiently, and ideally more cost effectively will compete better. Different skills are required to manage and service the more complex autonomous system. While the equipment suppliers could potentially provide many of the skilled resources from their experience during trials of autonomous trucks at other mines, it could be at the peril of the late adopter's current employees. If the late adopter mine company plans to implement autonomous haul trucks at a new mine they could avoid the negative image related to major job loss, but the early entrant equipment manufacturer with a leading brand will likely try to capture almost all the value that comes with their autonomous haul truck.

Late adopter mining companies will likely try a similar strategy to late follower equipment manufacturers to overcome the challenges of quickly and effectively changing their operations and human resource skills to operate autonomous haul trucks in the future. Consider Syncrude and Suncor, two of the largest oil sand producers in Alberta, for example. Suncor has just started trialling autonomous haul trucks, so Syncrude and similar producers are probably considering their competing strategy. They could prepare by installing safety sensors that will also be required for the future control of autonomous vehicles, such as forward obstacle detection, adaptive cruise control and brake assist / collision avoidance. In doing so, their technicians will learn how to service the components and systems. Furthermore, select operators will be familiar with the tools that control the haul trucks, so that in the future they are ready to move into command centres where they will monitor several trucks instead of driving one. Installing these systems does not only prepare the miner for the future, but improves safety now. For example, an automatic braking system could have saved a haul truck driver's life, who neglected to engage the service brake when the primary speed control system failed and their truck gained excessive downhill speeds and lost control (Alberta Employment, Occupational Health and Safety 2009).

Upgrading haul truck equipment with sensors is just one example of how a late adopter could prepare to implement autonomous haul trucks quickly in the future. Another example is to demand open-source fleet management systems so that they can eventually have a more flexible and broader fleet of autonomous equipment, rather than locking in to the systems like early adopters. Ultimately, late adopters need to plan a strategy to compete with early adopters of autonomous haul truck technology.

11: Conclusion

Autonomous haul truck systems are gradually gaining momentum in the mining industry. The supply of manual and/or autonomous haul trucks comes from a concentrated set of large firms. The early entrants have being developing autonomous vehicle technology independently. A standards ware is unlikely since the technology is moving towards open source platforms. Although early entrants will try to be the brand leader and gain as much market share and market growth as possible before there is more competition. Therefore, a firms' success will depend on its capabilities to improve its value chain and continue innovating (Duncan, Ginter and Swayne 1998).

Within the past decade, several mines have started or planned trialling autonomous haul trucks. The demand for minerals is ever increasing especially with a growing population in developing countries seeking to improve their standard of living with new infrastructure. The supply of minerals comes from lower grade deposits forcing miners to take innovative action to reduce the associated cost of increased earth moving and processing. Autonomous haul trucks are one opportunity to make their operations more efficient by reducing labour and related costs. They have appeared first at large mine operations in developed countries where there is a shortage of skilled workers and labour costs are higher. Mining companies have announced plans to implement more autonomous haul trucks in the near future.

The three largest mining equipment manufacturers have introduced autonomous haul trucks, while there are at least as many that have not. The early entrants currently provide proprietary fleet management systems to control the autonomous haul trucks that they manufacturer. Followers will likely count on fleet management systems developed by third parties using open source platforms in order to provide less expensive and more flexible systems. The majority of car manufacturers have rallied behind open source platforms to provide connectivity between vehicles on public roads, which will support the development of autonomous cars in the future and indirectly the development of autonomous haul trucks.

Early entrants that become front-runners in the market share of autonomous haul trucks will likely allocate funding and other resources to protect their market share and maintain growth against competitors. They will focus on improving value chain activities such as service, marketing and sales, and distribution to pursue a cost advantage, for example, over late following competitors. Autonomous haul trucks could become a firm's "Star" of the growth share matrix shown in **Error! Reference source not found.**.

Figure 17: Growth Share Matrix

Source: Boston Consulting Group

The growth share matrix is a chart where a firm can plot a portfolio of its different business units or products based on their level of market share and market growth. A star is a firm's business unit with high market growth and market share. If a firm can remain a market leader as the industry growth slows, then that star business unit could become a cash cow. A cash cow is highly valued by a firm because of the cash it generates with little investment.

Eventually, cash cows will become non-profitable dogs as market share is lost to competitors. This could be the case for autonomous haul trucks as more competition enters the market due to open source platforms, as discussed earlier. Having a portfolio of products with different market shares and growth rates can balance a firm's overall cash flow for the long term. Therefore, early entrants that have become brand leaders in autonomous haul trucks are likely to use some of their income to fund research and development of new ventures that could also become future stars.

12: Appendix – Economic Analysis

This section provides the data tables building up to the net present savings figure in Chapter 5 (also shown at the end of the appendix).

Assumptions:

- The cost difference between 9 manual haul trucks and 7 autonomous haul trucks is negligible.
- Each manually driven trucks requires 4.2 full time equivalent operators for 24hr operation and vacation coverage.
- Each set of 9 autonomous haul trucks requires 4.2 full time equivalent command centre technicians.
- Set-up costs for each additional 9 trucks are 50% of the initial set-up cost described in Chapter 5.
- The truck life is 7 years.
- Other savings and costs besides fuel savings are less significant and not included in the analysis.

The following table indicates the annual savings and initial set-up costs for various numbers of replaced manually driven trucks at a truck driver salary of $100,000.

Manually driven trucks replaced	**9**	**18**	**27**	**36**	**45**
Annual Operator Savings	$3,360,000	$6,720,000	$10,080,000	$13,440,000	$16,800,000
Annual Fuel Savings	$1,000,000	$2,000,000	$3,000,000	$4,000,000	$5,000,000
Total Annual Savings	**$4,360,000**	**$8,720,000**	**$13,080,000**	**$17,440,000**	**$21,800,000**
Initial Set-up Costs	**-$7,000,000**	**-$10,500,000**	**-$14,000,000**	**-$17,500,000**	**-$21,000,000**

The following table shows the undiscounted annual and total savings for a mine with a truck driver salary of $100,000 per year.

Manually Driven Trucks Replaced	**Net Real Savings**	**Year**							
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
9	$23,520,000	-$7,000,000	$4,360,000	$4,360,000	$4,360,000	$4,360,000	$4,360,000	$4,360,000	$4,360,000
18	$50,540,000	-$10,500,000	$8,720,000	$8,720,000	$8,720,000	$8,720,000	$8,720,000	$8,720,000	$8,720,000
27	$77,560,000	-$14,000,000	$13,080,000	$13,080,000	$13,080,000	$13,080,000	$13,080,000	$13,080,000	$13,080,000
36	$104,580,000	-$17,500,000	$17,440,000	$17,440,000	$17,440,000	$17,440,000	$17,440,000	$17,440,000	$17,440,000
45	$131,600,000	-$21,000,000	$21,800,000	$21,800,000	$21,800,000	$21,800,000	$21,800,000	$21,800,000	$21,800,000

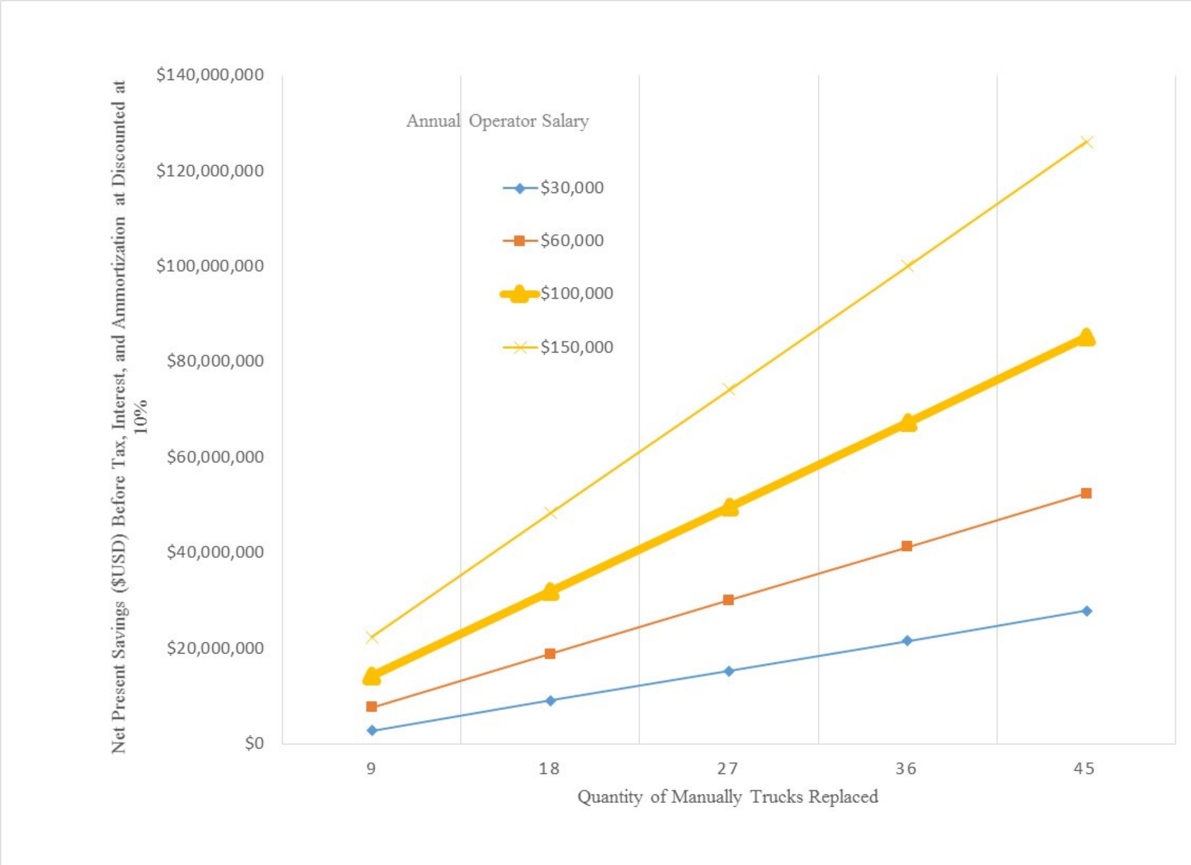
The following table shows the annual and net savings at a 10% discount rate for a mine with a truck driver salary of $100,000 per year.

Manually Driven Trucks Replaced	**Net Present Savings**	**Year**							
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
9	$14,226,306	-$7,000,000	$3,963,636	$3,603,306	$3,275,733	$2,977,939	$2,707,217	$2,461,106	$2,237,369
18	$31,952,612	-$10,500,000	$7,927,273	$7,206,612	$6,551,465	$5,955,877	$5,414,434	$4,922,213	$4,474,739
27	$49,678,918	-$14,000,000	$11,890,909	$10,809,917	$9,827,198	$8,933,816	$8,121,651	$7,383,319	$6,712,108
36	$67,405,224	-$17,500,000	$15,854,545	$14,413,223	$13,102,930	$11,911,755	$10,828,868	$9,844,425	$8,949,478
45	$85,131,530	-$21,000,000	$19,818,182	$18,016,529	$16,378,663	$14,889,693	$13,536,085	$12,305,532	$11,186,847

The following table provides the net present savings data points for the subsequent chart.

	Manually Driven Trucks Replaced				
Annual Salary	**9**	**18**	**27**	**36**	**45**
$30,000	$2,775,785	$9,051,570	$15,327,355	$21,603,140	$27,878,925
$60,000	$7,683,151	$18,866,302	$30,049,453	$41,232,605	$52,415,756
$100,000	$14,226,306	$31,952,612	$49,678,918	$67,405,224	$85,131,530
$150,000	$22,405,250	$48,310,499	$74,215,749	$100,120,999	$126,026,248

The following chart also shown in Chapter 5 indicates the simplified net present savings for replacing manually driven haul trucks with autonomous haul trucks for mines of various production ranging from 9 to 45 manually driven haul trucks and various driver salaries ranging from $30,000 to $150,000. The line representing the savings at $100,000 per year in salary is bolded to match the highlighted chart following it.



Net Present Savings ($USD) Before Tax, Interest, and Ammortization at Discounted at 10%
$140,000,000
$120,000,000
$100,000,000
$80,000,000
$60,000,000
$40,000,000
$20,000,000
$0
Annual Operator Salary
$30,000
$60,000
$100,000
$150,000
9
18
27
36
45
Quantity of Manually Trucks Replaced

13: Reference List

Accenture. 2010. *Using autonomous equipment to achieve high performance in the mining industry.* Accenture.

Alberta Employment, Occupational Health and Safety. 2009. *Worker Fatally Injured in Haul Truck Collision in Mine.* Alberta Government.

Anderson, James M., Nidhi Kalra, and Karlyn D. Stanley. 2014. *Autonomous Vehicle Technology: A Guide for Policy Makers.* Santa Monica: RAND Corporation.

Bergmann, Kym. 2013. "Mine of the Future." *Association for Unmanned Vehicle Systems International.* 03 November. Accessed February 19, 2014. http://www.auvsi.org/1132013/1132013MineoftheFuture.

BrandMover. 2009. *The first-mover Advantage.* May. Accessed 07 2014. http://www.brandmover.com/first-mover-advantage/.

Canadian Mining Journal. 2004. *Cat Improves MineStar Products.* 01 10. Accessed 07 07, 2014. http://www.canadianminingjournal.com/news/cat-improves-minestar-products/1000191859/.

CBC News Canada. 2013. *Distraction above impaired driving deaths in three provinces.* 19 08. Accessed 06 13, 2012. http://www.cbc.ca/news/canada/cellphones-blamed-as-fatal-collisions-by-distracted-drivers-up-1.1308025.

Chambers, Matt. 2012. *The Australian: Rise of the Machines.* 07 03. Accessed 06 21, 2014. http://www.theaustralian.com.au/news/features/rise-of-the-machines/story-e6frg6z6-1226291014017.

Chew, Andrew, Bruce Adkins, and Michael MacGinley. 2013. *Corrs Chambers Westgarth.* 17 May. Accessed February 17, 2014. http://www.corrs.com.au/THINKING/INSIGHTS/DRONES-AND-DRIVERLESS-TRUCKS-AND-LHDS-AUTOMATION-IS-THE-FUTURE-OF-AUSTRALIAN-MINING/.

Clemson University Vehicular Electronics Laboratory. 2014. *Automotive Electronics.* Accessed 06 15, 2014. http://www.cvel.clemson.edu/auto/systems/dsrc.html.

Duncan, Jack W, Peter M. Ginter, and Linda E Swayne. 1998. "Competitive Advantage and Internal Organizational Assessment." *Academy of Management Executive* Vol 12 No. 3 pp 6 - 16.

Fisher, Brian S., and Sabine Schnittger. 2012. *Autonomous and Remote Operation Technologies in the Mining Industry: Benefits and Costs.* Canberra: BAEconomics.

Freeport-McMoRan Copper and Gold. 2014. *Cerro Verde.* Accessed 2014. http://www.fcx.com/operations/peru_arequipa.htm.

Geology.com. 2014. *The Facts about Copper.* 25 05. http://geology.com/usgs/uses-of-copper/.

Goodbody, Ailbhe. 2014. "Insights Into Innovation." *Mining Magazine*, January / February: 12-16.

GPS. 2008. *Increasing GPS Accuracy.* 8 October. Accessed July 06, 2014. http://gps2008.wordpress.com/.

International Mining IM. 2012. "Automation and Remote Mining." *International Mining IM*, 01 January.

International Mining. 2011. *IM meets leading Chinese mining truck manufacturer XEMC in Brazil.* 28 September. Accessed 07 19, 2014. http://im-mining.com/2011/09/28/im-meets-leading-chinese-mining-truck-manufacturer-xemc-in-brazil/.

Katz, Michael, and Carl Shapiro. 1994. "Systems Competition and Network Effects." *Journal of Economic Perspectives* Volume 8, Number 2, pp 93 -115.

Lieberman, Marvin, and David Montgomery. 1988. "First-Mover Advantages." *Strategic Management Journal* 41-58.

Meech, John A. 2012. “Autonomous Haulage Trucks: The Future is Now.” *Automining: 3rd International Congress on Automation in the Mining Industry.*
Merriam-Webster Dictionary. 2014. *Automation.* http://www.merriam-webster.com/dictionary/automation.
Mining Magazine. 2014. “Fleet-footed.” *Mining Magazine.* 21 02. Accessed 07 19, 2014. http;//www.miningmagazine.com/equipment/fleet-footed.
—. 2013. *Icons of industry.* 29 Apr. Accessed Jun 27, 2014. http://www.miningmagazine.com/equipment/icons-of-industry?SQ_DESIGN_NAME=print_friendly.
—. 2013. “Caterpillar and Fortescue autonomous trucks update.” *Mining Magazine*, 04 October.
Mining.com. 2008. *Finning Announces C$360 Million Mioning Equipment and Support Services Deal with Suncor.* 07 05. Accessed 06 30, 2014. http://www.mining.com/finning-announces-c360-million-mining-equipment-and-support-services-deal-with-suncor/.
NHTSA. 2013. *Policy on Automated Vehicle Development.* 30 05. Accessed 06 11, 2014. http://www.nhtsa.gov/About+NHTSA/Press+Releases/U.S.+Department+of+Transportation+Releases+Policy+on+Automated+Vehicle+Development.
OECD. 2012. *Long-term Growth Strategies.* Economic Policy Papers, OECD Publishing.
Oleaga, Michael. 2014. “Apple vs. Samsung Sales Market Share.” *Latin Post.* 06 04. Accessed 07 19, 2014. http://www.latinpost.com/articles/10091/20140406/apple-vs-samsung-sales-market-share-inc-top-smartphone-google.htm.
Open Automotive Alliance. 2014. *Open Auto Alliance.* Accessed 2014. http://wwwopenautoalliance.net.
—. 2014. *Open Automotive Alliance.* 31 05. http://www.openautoalliance.net/#about.
Palumbo, Dr. Fred. 2014. *Second To Market... A Better Idea?* 28 05. http://commie.droryikra.com/v66i8/features/market.shtml.
Parreira, Juliana. 2013. *An Interactive Simulation Model to Compare an Autonomous Haulage Truck System with a Manually-Operated System.* PhD Thesis, Vancouver: University of British Columbia.
Penty, Rebecca. 2013. “Suncor Seeks Cost Cutting With Robot Trucks in Oil-Sands Mine.” *Bloomberg New Energy Finance*, 30 October.
Rio Tinto. 2009. *Diavid Diamond Mine.* Newsletter, Yellowknife: Rio Tinto.
Sharwood, Simon. 2012. *The Reigister.* 26 11. Accessed 06 21, 2014. http://www.theregister.co.uk/2012/11/26/autonomous_mining_trucks/.
Siciliano, Bruno, and Oussama Khatib. 2008. *Springer Handbook of Robotics.* Stanford: Springer.
Stuckey, John, and David White. 1993. “When and when not to vertically integrate.” *McKinsey&Company.* August. Accessed July 2014. http://www.mckinsey.com/insights/strategy/when_and_when_not_to_vertically_integrate.
The Economist. 2013. “Mining in Chile: Copper Solution.” *The mining industry has enriched Chile. But its future is precarious.* 27 04. Accessed 07 01, 2014. http://www.economist.com/news/business/21576714-mining-industry-has-enriched-chile-its-future-precarious-copper-solution.
Thurlow, Andrew. 2014. *Automotive News.* 7 May.
Walker, Simon. 2014. “Autonomy Gradually Gains Momentum.” *Engineering and Mining Journal*, 13 January.
Waze. 2014. *Waze.* Accessed 06 16, 2014. https://www.waze.com/.
Wenco. 2010. *Press Release: Wenco Signs Largest Ever Contract.* Ocotober. Accessed July 08, 2014. http://www.wencomine.com/our-press/wenco-signs-largest-ever-contract-2/.
Wunker, Stephen. 2012. “Better growth decisions: early mover, fast follower or later follower?” *Strategy and Leadership* Vol. 40 No. 2 pp. 43-48.