Automation of Load Haul Dump Machines

Anna Gustafson
Automation of Load Haul Dump Machines

Anna Gustafson
Department of Civil, Environmental and Natural Resources Engineering
Division of Operation, Maintenance and Acoustics
Luleå University of Technology
The research work presented in this technical report is part of the literature review within the InMaint Project (Integrated Maintenance for improved production and products) and has been carried out at the division of Operation, Maintenance and Acoustics at Luleå University of Technology. I would like to thank the Swedish Foundation for Strategic Research (SSF) and Sandvik Mining and Construction for providing financial support during my research.

I would like to thank my supervisor Professor Håkan Schunnesson and my co-supervisors Professor Diego Galar and Professor Uday Kumar for their invaluable support, good ideas and guidance during this research.
Load Haul Dump (LHD) vehicles are used in underground mines to load and transport ore and minerals. They can be manually or automatically operated. With an automatic system, the operator can be taken out of the mine and simultaneously control up to three LHDs, thus increasing both productivity and security for the personnel.

There are a number of operation modes available for Load Haul Dump (LHD) vehicles and there are many criteria to consider when choosing the best one. This report fills a gap in the literature by mapping and describing the experiences and present status of the operation and maintenance of both automatic and manual LHDs as well as the existing navigation systems and techniques associated with underground automated loading and transportation.

The commercially systems available today for automation of LHDs are supplied by Sandvik, Caterpillar and Atlas Copco. Automation focus have over the years gradually shifted from having fully automated fleets of vehicles to more flexible solutions with semi-automatic LHDs gaining safety as one of the main goals. Several issues must be resolved to maximize the benefits of automation. One is to improve maintenance, as this is crucial for an operation to work smoothly without the waste incurred by unplanned breakdowns.
CONTENTS

CHAPTER 1 - Introduction ................................................................................................. 1
  Purpose of the research study ....................................................................................... 1
  Objectives and limitations of the research study .......................................................... 1
CHAPTER 2 - Load haul dump machines and trucks ......................................................... 3
  Manual operation ........................................................................................................... 4
  Line of sight remote control ....................................................................................... 4
  Tele-remote control ...................................................................................................... 5
  Fully automated operation ............................................................................................ 6
  Semi-automatic operation ............................................................................................. 7
  Manufacturing companies ............................................................................................. 7
CHAPTER 3 – Navigation ................................................................................................. 11
  Absolute navigation ...................................................................................................... 11
  Reactive navigation ...................................................................................................... 12
  Environment ................................................................................................................ 12
  Requirements for underground navigation .................................................................. 13
  Underground positioning systems ................................................................................ 13
    Localization ................................................................................................................ 13
    Dead reckoning ........................................................................................................... 13
    Opportunistic Localization ........................................................................................ 14
  Commercially available navigation systems for LHDs .................................................. 14
    AutoMine .................................................................................................................... 14
    MINEGEM ................................................................................................................ 17
    Scooptram automation system ................................................................................ 18
CHAPTER 4 – Past experiences with LHD automation ..................................................... 21
  Prototypes and field tests ............................................................................................. 21
  Automatic tramming and hauling .................................................................................. 22
    LKAB, Kirunavara mine ............................................................................................. 22
    LKAB, Malmbeger Mine ........................................................................................... 23
    Lappland Goldminers AB, Zinkgruvan ..................................................................... 24
    BHP Billiton, Olympic Dam Mine .............................................................................. 24
    Codelco, El Teniente mine ........................................................................................ 25
    Newmont Mining Corporation, Jundee mine ............................................................. 25
    INCO, Stobie mine and Creighton mine .................................................................... 25
    Inmet, Pyhäsalmi mine ............................................................................................. 26
    Northgate Minerals Corporation, Stawell mine ......................................................... 26
    Rio Tinto, Northparkes mine ....................................................................................... 26
    Rio Tinto, Diavik mine ............................................................................................... 27
CHAPTER 1

Introduction

Automatic Load Haul Dump (LHD) machines are used in mines to improve productivity and increase the security of the mine’s personnel. With an automatic system, the operator can be taken out of the mine and simultaneously control up to three LHDs, with the possibility of increasing both productivity and security. As Poole et al. (1998) point out, when it is used in day-to-day operations, the automated process offers flexibility and convenience for the operators. In addition, the resulting health and safety benefits will lead to the long term wellbeing of the operators. There will also be manpower savings with less travelling time and the possibility of using one operator for multiple machines. Maintenance costs may drop as well: Mäkelä (2001a) says that a properly designed automatic machine will last longer since it requires less repair than a manual one. Other advantages of automation include process consistency and the ability to counter labour shortages (Chadwick 2010). According to Parreira et al. (2009) the main objective of automation is to imitate the maximum physical and intellectual human capacity to improve productivity through increased accuracy.

For LHDs, automation involves the following variables: laser equipment mounted onboard the LHDs, data processing features, broadband communications, sensors etc. The navigation techniques used for the underground LHDs differs slightly between systems but have the same purpose.

Purpose of the research study

The purpose of this report is to investigate the experiences and describe the present status of automatic LHDs and the existing navigation systems and techniques.

Objectives and limitations of the research study

The objectives of this research study are to:

- study experiences of automatic LHDs
• study experiences of maintenance of LHDs, paying special attention to automatic LHDs

• review all mines presently using automatic LHDs

• describe the navigation systems used for the automatic operation of LHDs

This study is mainly limited to the maintenance of, and experiences with, automatic LHDs in underground mining.
CHAPTER 2

Load haul dump machines and trucks

LHDs are used in most underground mines for the loading and transportation of ore and minerals. LHDs (figure 1) are usually 8 to 15 meters long; they weigh 20 to 75 tons, and they run on electrical or diesel power. They generally operate at a relatively low speed of about 20-30 km/h because the mine environment is often hot, dusty and wet. Each LHD consists of two parts connected by an articulation point; this gives them a high level of manoeuvrability in narrow mine drifts. Each section of the unit has a set of rubber wheels that are not steerable. The back of the machine contains the engine, and the front contains the bucket. The bucket, the steering and the brakes are hydraulically operated (Larsson 2007).

Figure 1  Load Haul Dump machine (courtesy of Sandvik)

Both LHDs and mining trucks (figure 2) can be used in underground mines and fitted with automatic systems. However, while the former have a bucket and can therefore load the ore/minerals, the latter can be used only for transportation. In open cast mining, it is common to use larger trucks than those used in underground mines.
Manual operation

Currently, manual operation (figure 3) of the LHDs is the most common way of moving ore in an underground mine. The operator remains in the cabin on top of the vehicle throughout the load-haul-dump cycle. The side position of the cabin makes it possible for the operator to have a clear line of vision when the vehicle is moving forward or backward. Because remote control offers limited sensory perception (Roberts et al. 2000), manual operation is faster than remote control and tele-remote control. The disadvantages of manual operation include lack of safety, driver fatigue and basic human errors (Roberts et al. 2000).

Line of sight remote control

An initial stage of automation is to operate the LHD by remote control while keeping it in sight. This technique is common practice in unsupported areas. An operator drives
the vehicle manually to the brow (entrance) and then dismounts to drive it into the stope by radio remote control. At all times, the operator is close by and can see the LHD. Once the bucket is loaded, the operator climbs back onto the machine to drive manually to the dump point. This procedure is slow because of the constant switching between manual and remote operation. It is also unproductive, as the operator’s limited view of the loading operation makes the bucket difficult to fill. Most importantly, it is not safe since the operator remains close to the remotely controlled vehicle and the unsupported ground (see figure 4).

Figure 4  Line of sight operation (courtesy of Sandvik) and a radio remote control (courtesy of Atlas Copco)

Tele-remote control

Tele-remote operation is the next step in automation and is slowly gaining acceptance in the mining industry. Here, video cameras are installed on the LHDs to provide the remote operator with clear views forward and backward. The LHD is remotely operated during the complete LHD load/dump cycle. An operator can be located in a safe and comfortable environment a long distance from the vehicle but can still operate only one vehicle at a time. The view is not always clear, as shown in figure 5, so it can be difficult for the operator to manoeuvre the machine.
Because of the limited sensory perception of the operators running the machines remotely, the speed of the vehicles is lower, and this results in decreased productivity. Although the tele-remote operation has led to improved safety, costs are increased because of the additional expenses of the infrastructure required for tele-operation (Dragt et al. 2005).

**Fully automated operation**

The next step in automation for LHDs is to allow them to drive autonomously. Operators are still required to monitor vehicles and must be involved at some points during the loading cycle, but they can operate one or several vehicles simultaneously from a safe environment. The operator's station can be located either outside the mine or inside the mine in a van or office. Since such vehicles will faithfully follow programmed instructions, management has the flexibility to control the performance of the vehicle and to influence its wear and tear.

It is useful to evaluate automated machines using Key Performance Indicators (KPIs), as these will determine both the positive and the negative aspects of the automated machines. Automation does not improve all KPIs; for example, cycle times for haulage trucks might increase if the driving speed is reduced for safety reasons. Yet the overall production can still be improved through shift breaks or shift changes (Parreira et al. 2009).

To ensure safety, the area where the automatic vehicles operate must be isolated by a physical barrier system (see figure 6). Any breach in the system will immediately stop the machines (Sandvik c).
Casteel (2008) points out some problems with automatic systems. For example, a mine needs to meet certain special physical requirements to benefit from an automatic system, and it is also very costly to install. Arguably, large-scale mining will obtain more significant benefits from installing an automatic system, as production can be increased in large cycle applications. Casteel notes that the system can be fitted to suit smaller operations as well, but it is easier to install the technology in mine sections that are designed with automation in mind.

**Semi-automatic operation**

Sandvik offers a semi-automatic system that increases the possibility for other applications where mobility is required, like open stope mining and transfer level applications. Other manufacturers have developed similar semi-automatic systems. The semi-automatic LHD can be used in the same way as the fully automatic LHD, but it can also be used manually when it cannot be run in the automatic mode. The automatic system used for semi-automation is different than the fully automated system: less infrastructure is needed, and only one operator is required for each vehicle. The LHD has to be taught the route between the load and dump points when entering a new production area (Chadwick 2010). Since these systems are more flexible than the fully automatic solution, the operator’s station is usually underground in a van or office.

**Manufacturing companies**

Because of their wide usage in the underground mining industry, LHD machines are manufactured by a number of companies. The best known are Atlas Copco (formerly Wagner) and Sandvik (formerly Toro) from Sweden and Caterpillar (formerly Elphinstone) from the USA/Australia (figure 7-9). Each supplier offers a number of

![Electric Safety Lock](image1.png) ![Field Cabinet](image2.png) ![Zone Status Lights](image3.png)
different machine models with varying capacities and sizes. The first supplier to introduce automated systems for underground mining was Sandvik (Kral 2008).

Figure 7 Automated LHD system from Sandvik with the operator’s environment (courtesy of Sandvik)

Figure 8 Automated LHD system from Atlas Copco with the operator’s environment (courtesy of Atlas Copco)

Figure 9 Automated LHD system from Caterpillar with the operator’s environment (courtesy of Caterpillar)
Table 1 shows the three main producers of automatic LHDs and their automation software.

Table 1    Manufacturers of automation systems and LHDs

<table>
<thead>
<tr>
<th>Brand name</th>
<th>Producer company</th>
<th>Producing country</th>
</tr>
</thead>
<tbody>
<tr>
<td>AutoMine\textsuperscript{TM}</td>
<td>Sandvik</td>
<td>Sweden</td>
</tr>
<tr>
<td>MINEGEM\textsuperscript{TM}</td>
<td>Caterpillar</td>
<td>USA/Australia</td>
</tr>
<tr>
<td>Scooptram Automation</td>
<td>Atlas Copco</td>
<td>Sweden</td>
</tr>
</tbody>
</table>

In the past, automation systems were developed by mining companies with large research departments, like LKAB in Sweden and INCO in Canada. Today, research and development are mostly done by manufacturers who specialize in automation.
To operate autonomously, LHDs require a navigation system. The development of these systems began in the 1990s through such navigation techniques as:

- buried wires in concrete roads (Eriksson and Kitok 1991)
- optical markers in the tunnel like painted white lines (Kumar and Vagenas 1991) on the tunnel floor or ceiling or retro reflective tapes (Wylie 1996)
- rows of lights (Brophey and Euler 1994)

Each system had drawbacks that made it difficult to implement. A further stage of development included positioning 2D laser scanners to determine the position of a vehicle on a predefined path and reflective beacons in the tunnel (absolute navigation). Another navigation technique determined the position of a vehicle on a predefined path and its distance from the mine tunnels and surroundings (reactive navigation).

**Absolute navigation**

Absolute navigation is a technique used when navigating according to a predefined path defined by a set of coordinates in a coordinate system. The origin is defined in the environment in a static location and not in the moving robot. This method implies that both the navigation and the guidance functions are dependent on the localization functions at all times. The vehicle is totally blind to its environment and is dependent on its ability to stay close enough to the predefined path to avoid hitting any walls. Any obstacles not present in the original map will be run over since the system cannot adjust its path. As Roberts et al. (2002) explain, the main problem is that the estimated position is used to keep the vehicle on the right track. The problem can be avoided if the system is enhanced by the inclusion of an obstacle avoidance function (Larsson 2007).
Reactive navigation

Reactive navigation does not need a predefined path for the vehicle to find its way. Rather, the surroundings are observed by appropriate sensors, and the information gathered by the sensors is used to navigate. Since the tunnel itself is used for navigation, there is no need to install infrastructure to control the machine (Larsson et al. 2008). Duff et al. (2002) have tested a reactive navigation system in a mine and describe the three functional software layers in the automatic system as follows:

- **Operational level**: Accepts speed and steering set points from the operator.
- **Tactical level**: Controls both the speed and steering of the vehicle. The operator acts as a co-pilot and provides hints to the tactical layer, thus influencing behavior at decision points.
- **Strategic level**: Interprets a mission and generates the appropriate hints to the tactical level, which in turn generates the appropriate speed and steering demands to the operational layer.

The operation modes of the automated system are visualized in figure 10.

![Figure 10 Operation modes of the automated system (Duff et al. 2002)](image)

Environment

According to Dragt et al. (2005), the environment for automated guided vehicles (AGVs) is theoretically divided into indoor and outdoor environments. Underground mining most closely fits the theory behind the indoor environment because it is a two-dimensional environment with walls and floors, but it lacks vertical elevation. Since maps are already available at all underground mines, the indoor comparison becomes even stronger. Roberts et al. (2002) say it is possible to use the indoor mobile robot navigation techniques for LHDs working underground since most underground tunnels have rectangular cross-sections and a map.
Requirements for underground navigation

According to Baiden (2001), requirements for automation are telecommunications, positioning, navigation, equipment, software, electronics, mining engineering and organization. These must be considered if a mine wishes to automate its LHDs.

Underground positioning systems

All existing navigation systems for autonomous LHDs use some sort of laser-based positioning with onboard laser scanners to measure the distance and/or bearings to a set of reflective beacons or tunnel walls to determine the position of the vehicle. Localization and dead reckoning are also used.

Localization

Localization means that the absolute position of the vehicle is known at all times, unlike a fixed real-world coordinate system. In the real world system, there is a predefined path (a map of the mine) that the vehicle must follow. One problem with this method is that, in order to follow a predefined path, the vehicle must use its estimated position to go forward. With the detection of natural features like tunnel profiles, the estimated position is periodically corrected (Roberts et al. 2000). The estimation of the vehicle’s absolute position is often made by fusing data fusion onboard sensors and external measurements like odometry (Dragt et al. 2005). Localization is a challenge since the mine tunnels constantly change (Larsson et al. 2008).

Dead reckoning

Dead reckoning is the method of counting the number of wheel rotations and the direction of the vehicle. A gyro is usually helpful to determine the direction, and odometers mounted on the wheels help to determine how far the vehicle has moved. The system is calibrated regularly to certain reference points in the mine. It is important to know if there is any wheel slippage to determine how far the vehicle has travelled. One problem with estimating the vehicle’s course using dead reckoning is that the errors in positioning grow with time since the new positions are based on previous positions. This method requires periodical correction (see figure 11) of the accumulated drift to avoid rapid deviation (Larsson 2007). The simplest form of dead reckoning is odometry, in which the rotation of the wheels or the track of the robot is measured to estimate the robot’s motion (Mäkelä 2001b).
Opportunistic Localization

Opportunistic Localization is a method used for reactive navigation and is based on the understanding that it is only when a change occurs (for example, coming to an intersection) that a vehicle needs to determine its location (Duff et al. 2002). The vehicle does not need to know any absolute positions while driving in, for example, a straight tunnel. It is only when it comes to an intersection or something similar that it needs further information (Roberts et al. 2002).

Commercially available navigation systems for LHDs

The following three navigation systems are used for the automation of LHDs in mines today:

- AutoMine, developed by Sandvik together with Finnish universities
- MINEGEM, developed by Caterpillar together with CSIRO and Australian universities
- Scooptram automation system, developed by Atlas Copco

Two main techniques are used in the automation of LHDs, absolute navigation (used by AutoMine and previously SALT IV) and reactive navigation (used by MINEGEM and the Scooptram automation system). In both, the tramming and dumping are fully automated while bucket loading requires tele-remote operation. Previous systems required infrastructure installations but it is undesirable to have a lot of infrastructure to install, chiefly because the nature of the tunnels changes. Further, to install infrastructure, people must work in a hazardous environment (Dragt et al. 2005).

AutoMine

The AutoMine system (figure 12) is designed to be an automated loading and hauling system for underground mining. The system has several self-learning functions. If an
automatic LHD runs over a large rock, for example, the system will place a restriction on speed in that area, so the following machines either stop at the place of the rock or slow down, with a subsequent reduction of failure. The AutoMine system can be adapted to specific customer requirements, including:

- **PCS** – Production Control System, for planning, optimization of production execution and understanding of production inputs and outputs.

- **MCS** – Mission Control System, supervisory system controlling and monitoring the autonomous operations, including traffic management and providing the remote operator’s user interface.

- **MineLAN** – Broad band, high speed, data/video communication system for connectivity to automated underground LHDs and trucks as well as associated equipment.

- **Onboard automation systems** – For machine control, monitoring, and navigation.

- **ACS** – Access Control System, for isolating the autonomous operating area to ensure safety of personnel. (Sandvik b)

![AutoMine system overview (courtesy of Sandvik)](image)

Automated tramming is based on absolute navigation (dead reckoning and natural landmarks in the mine) but is not dependent on artificial infrastructure (Larsson 2007). Sandvik Mining and Construction has, together with Navitec Systems Oy developed a Mining Positioning and Guidance System, InfraFREE, for the automation of LHDs. The system does not require infrastructure installation and uses only onboard sensors to determine the machine’s position and orientation. An external mission control system determines how the machine should drive, based on its position and orientation. The system is being used at El Teniente, the Finsch mine, the Pyhäsalmi mine and the
Williams mine. The InfraFREE system uses information about the environment that has been programmed into it so the vehicle can determine its position by interpreting various environmental factors (Navitec systems). After the profiles of the walls are investigated using laser scanners on a manually operated LHD, the InfraFREE vehicle can drive autonomously, using the previously recorded data as reference (Eriksson 2001).

The AutoMine package contains the following:

- A navigation system that continuously determines the location of the machine and controls the autonomous tramming and dumping operations. The system uses laser scanners to scan tunnel wall profiles to verify machine position and does not require additional infrastructure.
- An onboard video system to provide the high-quality video necessary for tele-remote operation.
- A Wireless Local Area Network (WLAN) mobile terminal to provide the radio link between the machine and the communication system installed in the autonomous production area. (Sandvik c)

From the operators’ station which located in a safe environment inside or outside the mine, this system can be used to:

- Plan and monitor production
- Operate machines tele-remotely
- View machine operation information, such as alarms, measurements, gear selection, engine RPM and tramming speed
- Monitor and operate the barrier system
- Control and supervise the fleet
- Generate production and condition monitoring reports. (Sandvik b)

The AutoMine system allows the operator to focus on production. It also simplifies troubleshooting for service technicians during maintenance and diagnostics.

Two new products have been released by Sandvik: AutoMine-Lite and OptiMine (Sandvik b). AutoMine-Lite focuses on automation for single machines for open stope mining and applications for transfer levels (Sandvik c). The difference between line-of-sight operation and AutoMine-Lite is that in the latter, only the loading is remotely controlled, while in the former, the whole load-haul-dump cycle is remotely controlled, while the tramming and dumping are autonomous. AutoMine-Lite is designed to fit small scale installations and is more flexible than the traditional AutoMine system. The system can also be used to make the LHD semi-automatic. AutoMine-Lite is presently being operated in the Pyhäsalmi mine in Finland and has
recently been installed in LKAB’s mine in Kiruna, Sweden. The system is safer and more efficient than tele-remote control and radio remote control systems. With its set of functionalities and adaptive system, AutoMine-Lite provides unique opportunities in the field of automated mining; it opens new windows to safety and productivity that cannot be achieved with existing set-ups. It is an advanced alternative for tele-remote and radio remote control systems. AutoMine-Lite is based on the proven AutoMine core technology and is available for a vast range of Sandvik LHDs. Its flexible and modular system offers complete working safety, ease of operation and high level productivity making LHD automation available for more mining applications (Sandvik). For its part, the OptiMine system is designed for condition and production monitoring and suited for manually operated LHDs (Sandvik).

MINEGEM

The automated system MINEGEM is designed to take humans out of the mine and reduce the risks associated with the manual operation of LHDs. Even when machines are tele-operated, there are huge safety risks since safety procedures are not always considered. The MINEGEM system fits a standard LHD and can be run with either a co-pilot or an auto-pilot. The LHD can perform tramming and dumping and can return to the loading point using the automated system. In the co-pilot mode, an operator steers the vehicle from a control room, using a joystick to control the machine’s direction. In the auto-pilot mode, the LHD can be sent by the operator to a specific goal; it arrives there using a self guidance system. An operator is able to handle several machines simultaneously in the auto-pilot mode. A manually driven LHD could perhaps go faster than an automatic LHD, but the automatic LHD will not hit the walls. And since the machine does not need breaks in the same way a human does, production can be improved over 24 hours (Caterpillar 2008a).

MINEGEM was launched in 2004 exclusively for Caterpillar. The system is based on reactive navigation and opportunistic localisation which means there are no predefined paths. Rather, the system reacts to the environment and the tunnel walls and decides how to respond. A map of the underground structure is built up and compared to an abstract map as the vehicle moves forward. Information is constantly being evaluated. The system tolerates errors in position as well as lack of traction and can easily find the right course. Productivity increases of 40-60% have been reported for mines using MINEGEM instead of manual operation. There is also less wear and tear, as the machine is driven according to the manufacturer’s specifications and is not subject to the operator’s skill and decisions (CSIRO).

MINEGEM uses laser detection and a ranging system (LADAR) to give information about the vehicle’s position to the operator. One LADAR unit is placed in the front and one in the back of the LHD. Through a combination of on-board computers, cameras, lasers and operator station software, the LHD is prevented from hitting the walls. The operator can get audio feedback from the machine and has a clear view since two cameras are installed on the LHD, one in the back and one in the front (Caterpillar 2009). The LADAR system provides information to the LHD by comparing the scanned profiles with already existing profiles in a database created from the mine map. Based on the information received, the system can make a decision and
give commands, such as move forward, backward, maintain steady speed, accelerate or brake (Caterpillar 2008 a).

Like Sandvik’s AutoMine-Lite, the MINEGEM system can be used for small scale mining and semi-automation. Unlike tele-remote and line-of-sight operations that must operate in first gear, the machines operating with MINEGEM can run in second gear, thus increasing speed and productivity (Chadwick 2010).

**Scooptram automation system**

The Atlas Copcos Scooptram automation system (figure 13) is used for autotramming and dumping with on-board sensors and advanced software to control the vehicle. The vehicle follows a pre-recorded path while driving that is verified, approved and certified for production by the off-line Route Manager software. The operator’s station can be located in a safe, comfortable environment. Cameras are placed at the front and back and inside the cabin. The sensors (figure 14) are two laser towers with lasers, two antenna, an inertial measurement unit, an odometer wheel including inductive sensors and hinge angle encoders to control steering and boom position (Atlas Copco 2009 a). The communication system is a standard WLAN. When starting the automation process, the operator drives the vehicle along the actual path so the sensors can capture data and define the mine environment. The Route Manager then verifies and approves the recorded path. The collected data are used for orientation in the mine when the vehicle drives in automatic mode (Atlas Copco 2009 b).

![Scooptram automation system](image-url)
Figure 14 The sensors used for the Scooptram automation system (Atlas Copco 2009 b)
CHAPTER 4

Past experiences with LHD automation

Automatic systems have been used successfully by several mining companies for such applications as trampling/hauling and dumping. A few tests have used automated bucket filling but none has been very successful. The usage of an automatic LHD for backfilling operation has also been tested. Mining companies generally use the automatic system mainly for trampling and hauling and tele-remote control to load the buckets (Dyson 2008, Mining-technology.com).

Prototypes and field tests

In the late 1980s Vagenas (1988) performed several case studies simulating automated LHDs and compared the results with manually operated LHDs. In 1996, a project began to test different sensing options for an LHD at the Mount Isa mine in Queensland, Australia. In May 1999, the LHD began running at full speed in the test mine, and the LHD was taken to a real mine for testing. Here, the LHDs were able to operate at full speed through a typical production cycle (Roberts et al. 2000). Kall und Salz carried out a project with automatic LHD/truck prototypes. They used laser scanning equipment normally used by aircraft and LHDs from the German firm GHH (Woof 2003).

A benefit of tele-operation is improved maintenance, as the machine is operated within its capability. To test this theory, Cambrian college built a sophisticated mining machine model (1/4th scale model LHD) with the same telecommunication system as the machines currently working at Inco Limited (Baiden 2004).

Two different Atlas Copco LHDs were used in an extensive field trial in the Kvarntorp mine (Atlas Copco testing facility), Sweden, from 2006 to 2007. The test was first conducted with an Atlas Copco ST1010C LHD and later with an ST14 LHD. The purpose was to design an infrastructureless guidance system for the LHDs which was robust, fast and reliable. The results were compared with previous recorded manual operators. Based on a large number of repeated trampling operations, the system was found to have high reliability. Figure 15 shows the Atlas Copco Wagner ST1010 LHD that was rebuilt for automation tests in the Kvarntorp test mine. The following sensors
were added: a hinge angle encoder, a laser range finder for each direction of travel and a drive shaft encoder to measure drive length (Larsson et al. 2008).

![Automatic LHD system from Atlas Copco (Larsson et al. 2008)](image)

Figure 15  Automatic LHD system from Atlas Copco (Larsson et al. 2008)

**Automatic tramming and hauling**

**LKAB, Kirunavaara mine**

SALT I: In 1987 LKAB started a project together with ARA (now Sandvik). The objectives were to create driverless machines and remote/automatically controlled LHDs operated from a control room. The project did not meet these objectives and was shut down in 1991. The availability of LHDs was low, and the expected production level was not reached (Hedman 1998).

SALT II: In co-operation with Tamrock (now Sandvik), LKAB conducted a full scale test of LHDs equipped with a guidance system in the late 1980s. The LHDs brought nearly one million tons of iron ore to the shafts during the test period. The results were satisfactory but failed to meet the production and availability goals. During the test, sub level stooping was used as production method, rather than the sublevel caving that is presently used. The main conclusion was that it would not be cost effective to implement a technology based on infrastructure. However, the test provided input to economic simulations (Bergström and Wigden 1998).

SALT III: In 1995, a project involving several companies set out to create an autonomous system on level 1045. The personnel at LKAB had a positive response to the new system (Hedman 1998). In October 1998, the first semiautonomous Tamrock 2500 was delivered to LKAB in Kiruna, Sweden. In late 1998, full scale testing of the operation and monitoring of autonomous Tamrock Toro 2500 LHDs was performed (Bergström and Wigden 1998). The goal was to improve the utilization of LHDs and to have one operator controlling up to three LHDs. Use of the autonomous system led to improvements in productivity. One significant improvement was increased tire life, thanks to the smoother rides of autonomous LHDs. The autonomous LHDs also dropped fewer rocks. Even though tires, transmissions and other components were not damaged as frequently, LKAB expected even better maintenance results when the system was improved. To this end, two navigation systems were fitted to each LHD, and the machines worked on a 21-day cycle, with 19 days of operation and 2 days for
LKAB has more than 20 years of experience with automatic solutions that include automatic driverless trains and remote loading in the tapping galleries controlled from a central control room. When the experience at LKAB is compared with a predictive operating cost model, the conclusion is that the service and maintenance costs will be lower for the autonomic LHD since it runs more smoothly and has less frequent contact with the wall. The tire life is longer for an automatic LHD but bucket cost, fuel consumption per tonne of ore produced, oil and lubricant costs are about the same as for manual LHDs (Schweinkart, Soikelli 2004). For different reasons LKAB, Kiruna, stopped using automatic LHDs.

In 2011 LKAB will start using a Sandvik LHD (LH621) equipped with the AutoMine Lite system. The semi-automatic vehicle will be used instead of radio remote control. The initial focus will be on increased loading during the night and after blasting.

**LKAB, Malmberget Mine**

Malmberget mine is working with the MINEGEM team and the Swedish Caterpillar dealer Pon Equipment AB to try out a Caterpillar R2900G LHD for automated operation (Casteel 2008). Mine manager Björn Koorem says that production increased 10-20% with the automatic LHD. Two main advantages are safety (removing the operator from the mine) and ergonomics (operator working from a chair in a control room vs. uncomfortable seat underground). Other advantages like increased utilization and production and less machine damage will appear with time. The massive and slightly inclined ore body in Malmberget (LKAB) with its sub-level caving is a perfect fit for LHD automation. Interestingly, younger drivers have a slight advantage when starting the automatic driving since they have more computer experience and can compare the work to a computer game (Caterpillar 2008 a). Malmberget has also been operating a semi-automated LHD since 2007. The mine’s focus is on improving safety and increasing production during night shifts and after blasting.
In Zinkgruvan, Sweden, a 7-ton GHH model LF LHD was introduced 1999. The automated vehicle was equipped with cameras to detect the painted lines in the ceiling during tramming. Loading and dumping were remotely controlled by an operator from a control room. However, the mine found that the vehicle was in operation only about 40% of the time; external disturbances were the most frequent cause of downtime (Kumar and Vagenas 1991).

BHP Billiton, Olympic Dam Mine

BHP Billiton’s Olympic Dam Operation in Australia (ODO) is Australia’s largest underground mine; it has been involved in developing and testing automated LHDs since 1999, when a DAS system was fitted for testing onto an Elphinstone R.2900 LHD (which was very old). There were control problems when the speed was more than 5 km/hour. This was taken care of, and by April 2001, an R.2900 LHD was capable of speeds over 15km/hour on a test track. The DAS was installed again at ODO, but a week later, the LHD had an uncontrolled movement and drove 25 meters out of the production control area and through the safety barriers. It finally stopped in a stockpile, and before any analyses could be done, it shut down. The cause remains unclear but most likely it was a severe shock in the lowering of the bucket during loading, causing the computer onboard to crash. The system was redesigned and tested again in July 2002 (McHugh 2004).

A production trial at the 42 Orange 20 Stope (ODO) tested a new R.2900 LHD. The trial found that it generally took four shifts before the operators were comfortable with the system. The tramming and dumping were automated, and the speed was tested up to 20 km/hour. The autotram system could work through shift breaks, during major stope firings and through dust. The shift handover took only a few minutes above surface. The maintenance personnel commented that the automatic vehicles could drive faster (12 km/hour) than the manual ones (5 km/hour) when the roads were in bad condition, as operators could be injured driving on a bad road. A comparison was made between an automatic and a manual LHD driving on a road with good conditions during 15 cycles. The cycle times for the manual LHD were shorter than for the autonomous (McHugh, 2004). In 2003, ODO used two automated LHDs and reported an increase in production of 40% (CSIRO a). By 2009, the MINEGEM technology was being used for production at the ODO mines (Woof 2009). The test trial at the 42 Orange 20 Stope noticed that the bucket teeth would touch the wall if a corner was taken too fast. Otherwise, collisions with the walls were minor in the automated mode (McHugh 2004).

McHugh (2004) describes a four-month production trial of the MINEGEM system in 2002–2003 at Purple Stopes (ODO). The total system availability was over 90%. The main cause of downtime was the unreliability of the radio cell. Breakdown maintenance and oversize boulders were the biggest cause of utilization downtime. When comparing the autotramm operation with an average manual LHD, the trial found that the automatic LHD worked 1.9 hours more per shift.
In August 2003, at the 56 Amber 25 Stope, a second unit was fitted with MINEGEM. Two LHDs were operated in the same area and controlled from the surface by one operator (McHugh 2004).

**Codelco, El Teniente mine**

In 2003 two of Codelco’s El Teniente mining areas, Pipa Norte and Diablo Regimiento, were to be automated in several areas to increase productivity (Sandvik 2003). They used fully automated TORO 0010C LHDs, three in Pipe Norte and three in Diablo Regimiento (by June 2005) with the possibility of adding seven more. The LHDs were operated from a single control room (Schweinkart and Soikkeli 2004). The loading was carried out by tele-remote control, the hauling and dumping were autonomous and a guidance system together with a traffic management system controlled the units to the dump point and back (Sandvik 2003 and Schweinkart and Soikelli 2004). In 2004, the El Teniente mine in Chile was the first mine to use advanced autonomous LHDs in large scale production (Mining-technology.com). Woof (2005) notes that with the AutoMine system at El Teniente, more highly trained service personnel are required. However, over time, the automatic tramming will result in reduced machine downtime. There will be lower costs for maintenance and spares due to less wear and tear on drivelines, no overheated engines, optimized gear shifting and extended tire life. There will also be less bucket spillage and fewer collisions with the walls when using automated tramming. By 2009, only Codelco was using the full AutoMine system; it continues to do so at its Pipa Norte and Diablo Regimiento mines (Woof 2009).

According to Sandvik, as of January 2011, only Pipa Norte was using the automatic LHDs. Diablo Regimiento had stopped, as had Pilar Norte.

**Newmont Mining Corporation, Jundee mine**

Since the start of 2008, the Newmont Mining Corporation’s Jundee mine in Australia has successfully been using two automatic Caterpillar R2900s. The operator is responsible for the actual bogging using telemetry, and the rest is handled by MINEGEM. The mine has been able to use one less machine, thereby reducing operator costs while maintaining the same, or higher, production capacity. The wear and tear of the machines is less, and the machines stay off the walls and go faster with the automated system. The operators can be productive three hours more per day since they can operate the vehicle from outside the mine and do not have to travel out of the mine during blasting. The need for secondary piles in the mine has also been eliminated (Miningnews.net).

**INCO, Stobie mine and Creighton mine**

At INCO’s Stobie mine in Ontario, a “light wire” guidance system has been used successfully for several years. The operator handles up to three LHDs at one time. In 1999, INCO reported that six LHDs were used in its Stobie mine and two in its Creighton mine; they claimed improved service life and reduced maintenance and tire costs (Golosinski 2000). Time savings was a major benefit of automatic LHDs at
Stobie: two or three hours were saved per shift in travelling. When the LHD concept was implemented, the operators reacted positively to the change. A more precise prediction of failure could be made on engine, tires, frames etc. since the incoming data could be evaluated in a new way. Another benefit of autonomous LHDs was longer operation cycles for the machine (Hedman 1998). In 1997, a prototype Mine Operation Centre (MOC) was used to connect the Stobie mine, the Creighton mine and a research mine to test a tele-remote system including five LHD machines of various types. A MOC can also include maintenance functions (Baiden 2001). In the MOC test, benefits included reduced cycle times, lower costs and improved safety. The next step will be to apply tele-mining systems at Stobie; the first applications will be drilling and LHD operation. INCO is operating several LHDs from a control room; the loading is done via remote control, and the tramming and dumping are automated (Steele et al. 2001). In the Stobie mine, one disadvantage of autonomous LHDs is that the movement between the levels becomes more difficult when the cab is removed from the automated LHD because the operator has no place to sit (Hedman 1998).

Inmet, Pyhäsalmi mine

In 2003, Inmet’s Pyhäsalmi mine, Finland, started an automation project with Sandvik in which they tested Sandvik’s new technology. The company found that using the system resulted in better working conditions for the operators, increased safety and better ore recovery from the stopes. The capacity of the LHD was greater than with radio-remote control but lower than with manual operation. In January 2005, the new system was implemented in the mine; the flexible system was used in different stoping levels and routes with the operator station located in a van. The system came with movable access gates (Casteel 2007). The mine has been using one Sandvik TORO 11 automatic LHD since 2005 and added another in 2006 (Sandvik a). The mine is implementing the system in all new production levels and claims a 25% productivity gain over radio-remote control (Casteel 2007).

Northgate Minerals Corporation, Stawell mine

The Stawell gold mine in Australia, owned by Northgate Minerals Corporation, started using a MINEGEM system for an automatic LHD in August 2005. Since the working environment is bad, with high temperatures in a very deep underground mine, it is a big improvement to have an automatic LHD operation with an air-conditioned Mobile Operating station for the driver. The mine says that 50% or more of the material is being transported with MINEGEM-enabled machines and that the reliability of the system is 85-90% (Casteel 2008). The Stawell gold mine uses Caterpillar R.1600, R.1700 and R.2900 LHDs (Caterpillar 2007).

Rio Tinto, Northparkes mine

Rio Tinto’s Northparkes mine, Australia, has been using MINEGEM and claims that the availability of the system is more than 95% and that it is operating 10 hours per 12-hour shift (Caterpillar 2008 a).
**Rio Tinto, Diavik mine**

Rio Tinto’s Diavik mine, Canada, is very isolated; the only way to get there is by plane or in the winter by car. Because of its location, the mine is well suited for automatic machines. To increase safety and production and to lower the operation costs (Mining and Construction 2009), Diavik bought its first automatic Atlas Copco Scooptram ST14 in 2008 (Headway 2009). Since November 2009, Diavik has been able to operate the vehicle from a control room on the surface; it is the first Scooptram to be so operated. After a test period in a Diavik trial location, the system was used in a real underground situation. The operator’s station was located underground before they attempted to operate the machine from the surface. In order to evaluate if the automatic LHD performs as well as manual LHDs and has higher productivity over time, Rio Tinto will perform an acceptance test with chosen KPIs (key performance indicators) (Mining and Construction 2009).

**Boliden Mineral AB, Garpenberg mine**

Garpenberg mine, the oldest operating mine in Sweden, has signed a contract to buy three AutoMine-Lite automation systems and two Sandvik LH517 LHDs. There will be three operating stations, one in an office space and two mobile stations located in vans (figure 16). The installations of the systems were scheduled to start in late 2010 and expected to be completed for full production in the early 2011 (Sandvik d).

![Figure 16 Mobile operators station located in a van (Sandvik d)](image)

**Automatic loading and backfilling operations**

Dasys et al. (1994) have developed a relatively simple algorithm using "off the shelf" sensors to fill the bucket automatically. Other approaches have been tried but none has been applied to real production.

One problem with automatic loading is that some material is too difficult for the vehicle to pick up with a single bucket movement. Since not every scoop is uniform, the operator needs to use skill to load the bucket (Jobling-Purser 2006).
**Outokompo, Kemi mine**

Larsson et al. (2008) describe a field test in a mine in northern Finland in 2007–2008. Using an automated system, the ST14 (Atlas Copco) was working on a backfilling operation. Even though backfilling was not the system’s intended task, the initial results were very good, with flawless auto tramming. Mining & Construction (2008) says the vehicle was equipped with two cameras in the front and two in the rear, while three external cameras were mounted in the dumping and loading area. The vehicle had a laser scanner in the front and one in the back for scanning the walls up to 35 meters ahead. The real-time data of the vehicle’s exact position compared to the wall were provided by the laser scanners. The vehicle’s exact position in the mine was determined by the use of an ultra-precise steering algorithm and odometer. The vehicle was used to determine whether automated or manual backfilling was better. When there was a sudden collapse, the test machine began to assist in the real and dangerous backfilling operations. The automatic machine made a significant contribution.

**XSTRATA, Brunswick division**

The 1,125m-deep Xstrata mine, Noranda’s Brunswick division, is accessed by a vertical shaft and worked by two methods. The older cut-and-fill method allows the ore to be mined steadily from bottom to top and backfilled with waste rock, leaving a working platform. However, a second method, the more efficient open stoping is preferred. In this method, pillars are removed later. Blasted ore is retrieved by remote-controlled LHDs for transport to ore passes leading to one of the three crushing plants (Mining-technology.com). A project to develop an automatic loading system at Noranda began in 1990. The system was first tested on a Wagner ST-8B machine at Noranda’s Brunswick division in 1997. The automatic system was tested for a week and compared with the results of one good operator for bucket loads, mucking and tramming. The loads achieved with the automatic LHD were 4% larger than the loads by the remote control operation, and the automatic LHD filled the bucket 24% faster than the operator. A combination of the two yielded improved productivity, depending on the tramming time (Hedman 1998).

**BHP Billiton, Olympic Dam Operation**

A test trial was performed at the 42 Orange 20 Stope (ODO), using the Caterpillar Autodig to load the buckets; automatic tramming and dumping were also performed. After only three shifts, the Autodig was disconnected for three reasons. First, it was difficult to make a correct manual setting for the Autodig because of the large variations in rock sizes. Second, the Autodig managed to fill the bucket at one pass only about 30% of the time. Third, the Autodig would try to straighten out the machine while bogging on left full lock, causing the rear end to swing into the adjacent wall when reversing (McHugh 2004). When self-learning computers are accessible, the final phase with LHD automation can begin, namely, auto digging (Caterpillar 2008 a).
Summary of the mines using/have been using automatic LHDs

Several mines are presently using automatic LHDs. Some are testing automatic systems and others have used automation previously but have ceased for some reason or other. Figure 17 and Table 2 show these mines and their status with respect to the use of automatic LHDs and trucks. All mines that have been testing/using automatic LHDs have also been using LHDs with other operation methods, either in a different section of the mine or in the same section.

Figure 17  Mines using/have been using automated LHDs
Table 2  Overview of automated mines

<table>
<thead>
<tr>
<th>Company</th>
<th>Mine</th>
<th>Country</th>
<th>Using</th>
<th>Manufacturer</th>
<th>Automatic system</th>
<th>LHD/ Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teck Cominco and Barrick Gold</td>
<td>Williams mine</td>
<td>Canada</td>
<td>Presently</td>
<td>Sandvik</td>
<td>AutoMine Truck</td>
<td></td>
</tr>
<tr>
<td>BHP Billiton</td>
<td>Olympic Dam mine</td>
<td>Australia</td>
<td>Presently</td>
<td>Caterpillar</td>
<td>MINEGEM LHD</td>
<td></td>
</tr>
<tr>
<td>Boliden Mineral AB</td>
<td>Garpenberg</td>
<td>Sweden</td>
<td>Presently, starting up phase</td>
<td>Sandvik</td>
<td>AutoMine Lite LHD</td>
<td></td>
</tr>
<tr>
<td>Codelco</td>
<td>El Teniente, Diablo regimiento</td>
<td>Chile</td>
<td>Not currently in use</td>
<td>Sandvik</td>
<td>AutoMine LHD</td>
<td></td>
</tr>
<tr>
<td>Codelco</td>
<td>El Teniente, Pipa Norte</td>
<td>Chile</td>
<td>Not currently in use</td>
<td>Sandvik</td>
<td>AutoMine LHD</td>
<td></td>
</tr>
<tr>
<td>Codelco</td>
<td>El Teniente, Pilar Norte</td>
<td>Chile</td>
<td>Presently</td>
<td>Sandvik</td>
<td>AutoMine LHD</td>
<td></td>
</tr>
<tr>
<td>DeBeers Consolidated mines</td>
<td>Finsch mine</td>
<td>South Afrika</td>
<td>Presently</td>
<td>Sandvik</td>
<td>AutoMine Track and previously one LHD</td>
<td></td>
</tr>
<tr>
<td>VALE INCO Limited</td>
<td>Stobi mine</td>
<td>Canada</td>
<td>Stopped 2005/2006</td>
<td>Wagner</td>
<td>Light wire guidance system and truck</td>
<td>LHD</td>
</tr>
<tr>
<td>VALE INCO Limited</td>
<td>Creighton mine</td>
<td>Canada</td>
<td>Stopped appr. 2003</td>
<td>Light wire guidance system</td>
<td>LHD</td>
<td></td>
</tr>
<tr>
<td>Inmet</td>
<td>Pyhäusalmi mine</td>
<td>Finland</td>
<td>Presently</td>
<td>Sandvik</td>
<td>AutoMine Lite LHD</td>
<td></td>
</tr>
<tr>
<td>LKAB</td>
<td>Kirunaavaara mine</td>
<td>Sweden</td>
<td>On and off from the 80ies, have recently installed one semi-automatic LHD</td>
<td>Sandvik</td>
<td>SALTA, AutoMine Lite LHD</td>
<td>LHD</td>
</tr>
<tr>
<td>LKAB</td>
<td>Malnberget mine</td>
<td>Sweden</td>
<td>Presently</td>
<td>Caterpillar</td>
<td>MINEGEM LHD</td>
<td></td>
</tr>
<tr>
<td>Newmont Mining Corporation</td>
<td>Junee mine</td>
<td>Australia</td>
<td>Presently</td>
<td>Caterpillar</td>
<td>MINEGEM LHD</td>
<td></td>
</tr>
<tr>
<td>XSTRATA</td>
<td>Brunswick division</td>
<td>Canada</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northgate Minerals Corporation</td>
<td>Stawell gold mine</td>
<td>Australia</td>
<td></td>
<td>Caterpillar</td>
<td>MINEGEM LHD</td>
<td></td>
</tr>
<tr>
<td>Rio Tinto</td>
<td>Northparkes mines</td>
<td>Australia</td>
<td>Not in use, only tests</td>
<td>Caterpillar</td>
<td>MINEGEM LHD</td>
<td></td>
</tr>
<tr>
<td>Rio Tinto</td>
<td>Diavik mine</td>
<td>Canada</td>
<td>Was used during 2010, Presently stopped due to going underground</td>
<td>Atlas Copco</td>
<td>Scooptram automation LHD</td>
<td></td>
</tr>
<tr>
<td>Lappland Goldminers AB</td>
<td>Zinkgruvan</td>
<td>Sweden</td>
<td>1989-1990</td>
<td>GHH</td>
<td>Painted lines on ceiling</td>
<td>LHD</td>
</tr>
<tr>
<td>XSTRATA</td>
<td>Mt Isa Mines Ltd</td>
<td>Australia</td>
<td>Project on hold</td>
<td>Sandvik</td>
<td>AutoMine LHD</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 5

Maintenance

Poor machine reliability in design phase and human factors influence the occurrence of failures more than any other factors. The failure characteristics of the equipment and therefore the cost of maintenance are influenced by a single factor, namely, the designed reliability. More failures can be expected if a component or system has poor reliability. Mean time to failure (MTTF) is a simple measure of the arrival rate of failure. All failures have a cause and an effect; thus, after being identified, flaws can either be designed out or accommodated, thereby increasing the maintainability (Kumar 1990).

Woof (2009) states that automatic machines require less maintenance and have lower running costs because gears are changed at optimum times, and engines are not overrevved. Mining technology.com adds that maintenance requirements will be less for an autonomous system since the driving is always perfectly matched with the situation. As reliability and safety requirements are high, it is essential for a system to have a robust self-diagnostic fault detection and fail-safe mechanism in place.

Because of maintenance issues, INCO (Stobie mine and Creighton mine) cannot foresee having an entirely unmanned mine. Mining equipment is not very reliable, and the mean time between failures on components needs to be better before there can be less corrective interaction with the equipment (DeGaspari 2003).

Sandvik has installed several systems on its LHDs to make maintenance as safe as possible. All daily maintenance can be performed from the ground to avoid slips and falls. Preventive maintenance can be performed safely since there is an engineered access system around the unit to keep the exit safe at the top of the vehicle. Vehicles have been improved to facilitate maintenance and to increase the availability of the automatic machines in the following ways:

- Higher ambient temperature capabilities and longer component life are ensured by improved cooling.
- Reduced wear on the hydraulic system and improved reliability is ensured by the use of load-sensing hydraulics that deliver oil at the right pressure and only when needed to the different components.

- There is less fuel consumption because of the load-sensing hydraulic system.

- The main hydraulic oil is kept clean and the oil change interval is extended with the use of a separate tank for brake cooling.

- Without removing the bucket, Sandvik’s Ground Engaging Tool (GET) system facilitates fast renewal of the bolt-on wear parts which increases the bucket life (Chadwick 2008).

In the late 1980s, LKAB, Kiruna, performed a reliability investigation on a fleet of LHDs. Failure data from 19 LHDs were collected for a period of one year and analyzed, but because data were extensive, only the time between successive failures (TBF) for three machines was considered. The three machines studied were selected because of their age: neither too new nor too old. To calculate the TBFs, the LHD was divided into the following subsystems; engine, brakes, hydraulics and transmission. From a reliability point of view, the two most critical subsystems were found to be hydraulics and engines. When a machine was stopped for routine maintenance, the TBFs for these stops were treated asensored failures. Investigators concluded that the overall maintenance cost could be reduced through preventive maintenance of the engines (Kumar et al. 1989). The TBFs of the hydraulics were evaluated in a second study, using two years of data. At this time, old, medium old and new machines were studied (two of each). Results indicated that in most cases, the TBFs were neither independent nor identically distributed. Optimum maintenance policies were suggested (Kumar and Klefsjö 1990).

**Maintenance experiences**

A case study found that failures occurred in a LHD axle much sooner than expected, considering the number of operating hours. The results showed no component defects or deficiency but indicated that the failures corresponded to the use of a lubricant not suited for the climate. The expected life of both overhauled and new axles was met when the lubricants were changed (Carter 2007).

**INCO, Stobie mine**

Poole et al. (1998) describe how a RoboScoop W was modified so it could be autonomously operated at Stobie. Since the intent was to reduce the need for the operator’s presence, various applications were added to increase the time between daily maintenance/service. An auto lubrication system was also added. Since the machine was not dependent on the operator’s working hours, a “shift” for the machine could be based on either maintenance or service intervals.
**Codelco, El Teniente mine**

In El Teniente’s Pipa Norte mine, the LHDs only leave the production area when there is planned maintenance or a major breakdown. Refuelling and lubrication are scheduled by the AutoMine system and are carried out in a specific place where the LHD is taken by the maintenance personnel. Daily maintenance functions are performed while the machine is being serviced. The availability of the fleet is based on planned downtime hours (for scheduled maintenance services), and unplanned downtime hours (for unscheduled repairs or breakdowns). The unplanned downtime in an automatic operation is difficult to predict accurately. It is believed that with condition monitoring at least 15% of the potential failures can be identified and taken care of during the planned downtime. Downtime is believed to be about the same for the automated and manual machines. The number of full-time workers is estimated to be the same whether the fleet is autonomous or manually operated, although the required technical skill level is higher for an autonomous fleet. In the event of a breakdown, the LHD is prepared for manual control, and all other LHDs are excluded from that tunnel (Schweinkart and Soikelli 2004).

The automated system at the El Teniente mine requires more highly trained service personnel. The automatic tramming will, over time, result in reduced machine downtime. The costs for maintenance and spares are lower because there is less wear and tear on drivelines and no overheated engines, optimized gear shifting and extended tire life. With automated tramming, there will also be less bucket spillage and fewer collisions with the walls (Woof 2005).

**BHP Billiton, Olympic Dam Operation**

The production trial at the 42 Orange 20 Stope (ODO) noted that the underground maintenance crew took care of the re-fuelling at mid-shift according to the maintenance schedule. During re-fuelling, road maintenance was taken care of, and during service time, the lasers were cleaned with a rag (McHugh 2004).

**Maintenance experiences for manual LHDs and truck fleets**

**Underground mine, Canada, case study**

Vayenas and Xi (2009) performed a study in an underground mine in which they investigated the availability of 13 LHDs. They used both a basic maintenance approach and a reliability-based approach to determine fleet availability. They note that problems with inaccurate and incomplete data affected their analysis.

**Underground mine, Palaboura mine, South Africa**

This large block cave operation focuses on maintenance and the improvements in production that can be achieved with good maintenance. Because an LHD breakdown disrupts the whole production chain (Chadwick 2008), a good maintenance philosophy is essential. Therefore, Palaboura’s maintenance manager says that all machines have a 90 minute stop every day; at this time, everything is fixed. Even the most trivial fault is
taken care of since it could develop into a major problem if not fixed directly. Operators are assigned to specific machines, and this improves performance (Chadwick 2008).

**Underground mine, Chile, case study**

A case study in a gold mine in Chile analyzed failure data for a manually operated truck fleet to see if condition based maintenance could save money. Eleven scoops were involved in the study; Table 3 provides information on manufacturer, model and age (Hall et al. 2000).

<table>
<thead>
<tr>
<th>Description</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Year</th>
<th>Capacity</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scoop</td>
<td>Elscow Clarke</td>
<td>EBC-100</td>
<td>1990-1991</td>
<td>2 m³</td>
<td>7</td>
</tr>
<tr>
<td>Scoop</td>
<td>Wagner</td>
<td>ST-2D</td>
<td>1990</td>
<td>1.9 m³</td>
<td>2</td>
</tr>
<tr>
<td>Scoop</td>
<td>Picasso</td>
<td>9000</td>
<td>1994</td>
<td>5.1 m³</td>
<td>2</td>
</tr>
</tbody>
</table>

With respect to the relationship between the number of failures and downtime, the results indicate only a very small difference in the time it takes to repair a piece of equipment regardless of what has failed. The study expected to find that critical systems were responsible for a significant amount of downtime, but this was not the case. The relationship between number of failures and downtime was almost linear. Failure data showed that the number of machine-days lost due to maintenance was 956 for the fleet of scoops. Out of these, 617 machine-days were linked to repairs in hydraulics, engines and drive trains. Figure 17 shows the number of downtime hours for respective subsystems. For hydraulics, cylinders, oil leaks and valves were the primary causes of downtime. The study suggests that lack of spares and labour influence repair time (Hall et al. 2000).

![Figure 18 Scoop fleet failures (Hall et al. 2000)](image)

In their study of scoop fleet failures, Hall et al. (2003) analyzed maintenance data from 15 months. The maintenance personnel filled in maintenance cards, and the planning
clerk entered selected information from these cards into the maintenance management software package. The first part of the data analysis used pareto charts to find problem areas and select possible candidates for condition-based maintenance (CBM). The second part involved obtaining further information about the critical items found in the first part of the analysis. There were some problems with lack of data or data that were not recorded properly, like time between failures (TBF). The number of operating hours per day was 20.

Hall et al. (2000) investigated the condition-based maintenance of engines, using such techniques as spectrometric metal analysis, ferrography, gas chromatography and viscometry. The results showed that CBM was not performed properly, leading to significant costs. The authors also calculated the costs of planned and unplanned engine changes.

Hall et al. (2003) point out that because much of a mine’s equipment is mobile or semi-mobile it is difficult to formulate an effective maintenance strategy. Some factors influencing the maintenance costs of mobile equipment are:

- Increased number of failures due to disassembling and reassembling mobile equipment.
- Failures of mobile equipment in remote locations, making maintenance costly and difficult.
- Difficulties using condition-based maintenance on mobile equipment.

Other issues include the dynamic operating environment, the physical environment and the logistics. In addition, there are problems due to operator practices, varying production demand and changes within the ore characteristics. Useful data can be obtained from system sensors on mobile equipment, from operator interfaces and from operation and maintenance (Hall et al. 2003).

**Freeport-McMoRan Copper and Gold open pit mine, Sierrita, Arizona**

A maintenance program has been developed for trucks in the Freeport-McMoRan Copper and Gold open-pit mine in Arizona, USA. According to Caterpillar (2008 b), the mines operate 5 Caterpillar 793s, with the first starting in 1991. These trucks have achieved far more hours than expected due to, among other things, a structured maintenance process. The condition and availability of the trucks are very good. The mines find that to keep the equipment in the best possible condition, it is essential to have a thorough preventive maintenance (PM) program, perform fluid changes when required, monitor equipment condition and application and respond quickly and appropriately. The trucks have high availability for the following reasons:

- A few days before the vehicle is due for PM in the maintenance shop, it goes through an inspection so that all parts, special equipment and skilled mechanics are available when the truck enters the maintenance shop.
• The maintenance superintendent has high expectations, holds his people accountable and is always looking to correct even the smallest detail.

• The operation and maintenance staff work together to ensure that major breakdowns are avoided.

• A component replacement plan is followed. The replaced spares are sent to a rebuilding centre where they are rebuilt and put into another Caterpillar vehicle.

• A detailed planned component replacement (PCR) plan has been developed. The life expectancies of the component, the ongoing knowledge of its condition and what measures should be taken if there is a reduction in its performance and efficiency are defined. A PCR interval is set up for all components, both minor and major.

• The maintenance plan is not built on fixed intervals; rather, it is based on the component’s condition by, for example, monitoring the engines filters, oil condition and consumption, as well as its overall performance.

• A detailed condition-monitoring program is being used with the goal of changing components before failure occurs. Temperature, pressure and speed are currently being monitored.

• The maintenance coordinator keeps track of everything to do with the truck; component hours, truck hours, lubrication changes and the correct intervals for everything; the coordinator records information about services performed, work orders and scheduling etc.

• Contamination is controlled in two parts; first, fluid analysis/management monitors contaminants in fluids; second, maintenance process/environment cleanliness control monitors the cleanliness of the maintenance environment.

• There is active and detailed training of maintenance and operation personnel.

• There is good communication between operators and maintenance personnel.
Past experiences with truck automation

Inco, LKAB and Mount Isa Mines Ltd have pioneered the concept of truck automation. This includes loading from the chute, tramming to the dump point and returning to the chute. Even though Inco started working on the system in 1983 (the AHT-project), LKAB had its first truck working autonomously from 1986 to 1991. Between 1991 and 1993 (after that it was no longer needed) Inco operated a trolley-driven truck in the Stobie mine. The truck proved to have better availability and lower operating costs per hour than the truck working in Stobie (Golosinski 2000).

Teck Cominco and Barrick Gold, Williams mine

The Williams mine, Canada, has successfully used Sandvik’s AutoMine system since June 2007 (Mining-technology.com). The mine is using two Sandvik TORO 40 trucks for haulage (Sandvik a 2007). Williams Operation’s gold mine in Ontario has automated a truck that is being used to move 1500 ton per day (Golosinski 2000).

INCO, Stobie mine

The first truck to be installed in the Stobie mine was the “RoboScoop #1”, a Wagner ST-8B. Many people at Stobie had been injured and could not work underground. The automated system enabled them to work, thereby increasing productivity (Hedman 1998). The use of the “RoboScoop #1” was somewhat problematic, however. Although there were longer operating cycles between fuel stops, the fuel now had to be delivered to the machine instead of the machine being driven by the operator to the fuel base. It also became more difficult to move the vehicle from level to level without a proper place for the operator to sit (Poole et al. 1998).

DeBeers Consolidated Mines, Finsch mine

The Finsch diamond mine in South Africa, owned by DeBeers Consolidated Mines, is using automated trucks. The automated fleet consists of 6 automated T50D Sandvik Toro trucks with an additional 8 Sandvik 007 LHDs that are automation-ready. The trucks work in a dedicated tramming loop. Because the automated fleet can work at a
higher speed and in narrower tunnels, the trucks have higher throughput than those in a conventional fleet. Human error is eliminated, so the trucks are less damaged over time. At the moment, a limiting factor is the effect on production when a truck is undergoing maintenance or has had a breakdown. Initial problems with dust have been taken care of. The initial cost of the automated trucks was very high. An automated Sandvik 007 LHD is being tested to see if all LHDs at the 63 extraction level should be autonomous (Mining magazine 2007).

The Finsch mine has successfully used Sandvik’s AutoMine system since August 2005 (Mining-technology.com). In 2008, the Finsch mine had 1 semiautomated Toro 007 and 7 manually driven ones (Kral 2008). Kral says that each automated truck is equipped with an onboard video system in the front and in the back of the machine, thus enabling the operator to view the operation. During the tramming loop, the trucks are operated by computer-controlled laser scanners. The condition of each machine, as well as traffic from equipment operating in the same area, can be monitored at all times. Between its setup in 2005 and 2008, the automated system moved 16 000 tonnes per day of ore, compared with 15 000 tonnes per day for manual operation, from the Block 4 ore body. The production control system plans the optimal loading point for each truck to reduce waiting times and plans the optimal drawpoint for each LHD in order to reduce the vehicle stockings. The management system at Finsch consists of three parts; the Cave Management System (CMS), the Production Control System (PCS) and the Mission Control System. These systems work together for maximum control and efficiency. One advantage is that the trucks can move faster, 25 km/h, than a manually operated truck. Other proven advantages at Finsch are equipment health and greater productivity. The system is profitable in terms of labour savings, lower maintenance costs (bad driving habits and driver fatigue are no longer an issue) and round the clock operation.

The Operations Manager at Finsch, Mike Brown, comments that the system was not designed to save labour but to achieve increased efficiency. He believes that maintenance costs will be lower since the trucks are controlled by a computer which eliminates human error. There will be no bad driving habits or driver fatigue (Sandvik 2007).

The Finsch mine is special since it was designed with automation in mind. Most other mines are trying to fit an automated system into their existing operations. The benefits with automation have been increased safety at the mine, increased production and reduced wear and tear on the Toro 50 haulers. One problem is dust; since the mine is extremely dusty, the laser “eye” has to be kept clean. To this end, the washing fluid is refilled every maintenance period. The mine has reduced the re-oiling and refueling times from 20 to 5 minutes. The length of tire usage has increased and is reported to be about 5000 hours per tire. The hauling and dumping system is automated but the loading is done by tele-remote control. Finsch is the largest user of Sandvik’s AutoMine system (Dyson 2008).
Concluding remarks

Several mines have tested automated LHDs and transportation vehicles. Some have been more successful than others. In many ways, automation is good, especially with respect to safety, since the operator is taken from the machine and operates the LHD from a safe comfortable environment, either inside or outside the mine.

Despite their potential advantages, few navigation techniques have been successfully implemented. Many issues must be resolved to maximize the benefits of automation. One such issue is to improve maintenance so that the vehicle can operate smoothly, with a minimum number of unplanned breakdowns. If automated vehicles unpredictably break down at any time and in any location, it is difficult to run an optimized automatic operation.

At this point, commercial systems for automatic LHDs are available from Sandvik, Caterpillar and Atlas Copco.
REFERENCES


