EMESRT Design Evaluation Case Study 12-02

Evaluating Underground Mining Equipment Line-of-sight and Augmented Vision

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Abstract

Power haulage accounts for the greatest number of fatalities in Canadian, Australian, American, Indian, and Spanish mines, and is the fourth leading cause of fatal accidents in underground African mines. However, this rate is expected to grow with a move toward increased power haulage and less manual labour in Africa. Many of the fatal injuries have been associated with load-haul-dump (LHD) operation due to their notoriously poor line-of-sight (LOS) hampered by a sideways-seated operating position. To date, modifications to cabs, engine profiles, buckets, lights and, installation of rotated seats, have led to only moderate LOS gains. This case study reviews several approaches for LOS evaluation including computer simulation methods like the LOS boxplot. The benefits of a secondary viewing device to augment operator visibility are presented. A four-camera system was evaluated in a field trial. Placement of cameras to maximize LOS was determined on-site using field methods, and enhanced with immediate feedback provided by a custom written computer-based LOS assessment program. Prior to camera installation a 1.7m tall pedestrian was first visible to the LHD operator ~5m in front of the bucket, ~6m behind the engine and over 12m from the front right corner. With the optimized four camera placement and moderate operator head and trunk movement, a 360-view immediately around the LHD to a standing pedestrian height was realized. This case study provides further support for an augmented viewing system to improve operator LOS and illustrates the benefits of using computer-based options to evaluate LOS improvements.

Background

Over the last three decades mining methods have moved towards mechanization and automation. While this has generally reduced the number of serious injuries to miners, it has also increased the number of fatalities that result from the interaction of large pieces of machinery in small, confined roadways (Groves 2007; Kunar et al. 2010). Not only have the numbers of underground mining machinery increased, but there has been a concomitant increase in the size of the machines and payloads, in an effort to increase productivity. The machinery has also evolved to include full cabins rather than simple rollover protection systems (ROPS), and while these cabins provide full environmental protection, they also drastically limit the line-of-sight (LOS) from the operating compartment (Figure 1.1). The inability of the mobile equipment operator to clearly see pedestrians, objects, or hazards around the machine has contributed to a number of accidents resulting in equipment damage, lost work time, and fatal injury (MASHA 2006; NIOSH, 2001).

Canadian data published in 2001, by the Mines and Aggregates Safety and Health Association (MASHA) summarized accident statistics for LHD vehicles in the Ontario mining industry over a 15-year period between 1985 and 2000. During this period, 1690 accidents involving LHD vehicles were reported and poor LOS was identified as a causal factor in 24% of these accidents. Hitting pedestrians, mine walls and other vehicles accounted for 16% of all accidents while unseen ground hazards (potholes, muck on the ground or falling into holes) accounted for a further 8% of these accidents (MASHA, 2001). Powered haulage continues to have the 3rd highest injury/fatality rate for the time period of 2005-2009 in Ontario, Canada (WSN, 2011). Coroner’s inquests in Ontario, Canada continue to provide evidence that the LOS problem for seated drivers of mobile mining equipment has not been adequately addressed (OMSG 2009).
Figure 1: Example LOS from the LHD operator’s position. The LHD vehicle operator is unable to see a 5’6” pedestrian twenty feet away from the cab. Also, the mine floor only becomes visible 90 feet away from LHD vehicle operator.

A recent review of MSHA records suggests that the general category of equipment represents the highest number of fatalities between 1995 and 2004, and further, that fatal injury to miners was four times higher than the average rate for other industry (Groves, 2007). Powered haulage represented 8% of the more than 190 000 accidents but along with the machinery category accounted for 51% of fatal incidents (Groves, 2007). This was higher than the reported values from the 1986-1995 NIOSH data (NIOSH, 2000), and suggests that more work must be done to improve operating conditions for mobile equipment operators. The two most frequently used machines in underground mining, the haul truck and LHD, accounted for 16% and 9% of fatalities (Groves, 2007).

Burgess-Limerick (2011) makes a case for the importance of removing pedestrians from the areas where continuous miners and other large mining equipment is operating by identifying that being struck by, or caught between these machines represent frequent accident causes in Australian mining.

Internationally, a review by Michelo et al. (2009) found injury rates in Zambia mines to be lower than other African countries but higher than most high-income countries (USA, Australia, Canada, South Africa). The category of powered machinery ranked fourth for injury occurring in underground mines and accounted for 12% of overall injuries (and no fatalities) but the lower rate of mechanization may be keeping these numbers lower for the moment (Michelo et al. 2009). Indian coal mines ranked machines (including LHDs) as the leading cause of fatalities at 19.5% (as cited by Kunar et al. 2010). In Spanish mines, 13.7% of serious or fatal accidents were caused by being run over or hit by machines (Sanmiquel et al. 2010). Mobile machinery for underground use are designed with careful consideration to the physical constraints of the mining environment, which include low vertical and horizontal clearances, and the machinery is rarely designed to maximize driver sight lines.

The bulk of injuries in underground mining occur on the ubiquitous Load-Haul-Dump (LHD) machine (Burgess-Limerick et al. 2011), a machine that requires the operator to maintain a sideways-seated position, which further restricts their ability to see people, objects or hazards around the machine (Jeffkins et al., 2004). In response to the reported fatalities among operators of underground mobile machinery, past research has focused on identifying machine components and driving scenarios that lead to decreased LOS on LHDs (Boocock et al., 1996; Boocock and Weyman, 1994; Eger et al., 2004; Godwin et al., 2008). Marx (1987) found that the following variables influenced viewing conditions: vehicle outline and orientation of outer corners, obstructions caused by air filters, tanks and other add-ons, proper lighting of working conditions and canopy/cabin support structures. Rushworth (1996) listed canopy supports, fixed seat positions, headlights, mudguards and hydraulic control units as being responsible for restricted forward sight lines.

Eger et al. (2004) reported that complete blind spots were linked to cab posts, the back of the operator cab, lights and light brackets. An operator questionnaire further identified wheel well covers, bucket lip shape or oversized bucket, light posts, radiator cover, booms and hoses, engine style, air intake cylinders and add-on features such as fire extinguishers and radio remote boxes to be related to restricted LOS (Eger et al., 2004). Once the design of the machine was identified as less than optimal for safe and efficient operation, several investigations attempted to identify the components most likely to produce a substantial improvement to LOS. Although some innovative ideas have been presented, more than one research group has suggested that a complete redesign of the mining machine concept would be required to substantially improve LOS (Godwin et al. 2007; Schutte and Shaba, 2003).

The information available for other types of underground machinery is not as extensive, but haul trucks in general (underground, surface, open-pit) have been recognized to be the single-most hazardous piece of mobile mining equipment, causing 22.36% of mining equipment fatalities in the United States (Kecojevic, 2007). It is known that underground haulage trucks contribute to those overall numbers of mine fatalities (Kecojevic et al., 2007; MSHA, 2009).

Poor operator LOS resulting from machine design appears to be a contributing factor in a significant number of equipment-related fatalities. For this reason, measuring and evaluating LOS continues to play an important role in understanding how industry can reduce the incidence of accidents involving
mobile equipment. This case study describes several computer-based options for measuring operator LOS, and introduces the evaluation of a secondary viewing aid using these methods.

**Evaluting Line-of-Sight**

Several standards have been developed to evaluate earth-moving machinery, including the International Organization for Standardization (ISO) 5006-1, which evaluates masking widths on a 12m radius circle at ground level as well as a rectangular perimeter located 1m away from the machine at a height of 1.5m. The machine is considered to have acceptable or unacceptable visibility based on the number and width of the masking shadows. The Society for Automotive Engineers (SAE) has created a variation to the ISO 5006-1 standard, labeled XJ1091. The Forest Engineering Research Institute of Canada (FERIC) developed a similar method to the ISO 5006-1 Standard to measure visible and non-visible areas around a 12 meter radius using a mirror mounted on a 45 degree angle measuring stick (Golsse, 1994).

Research by Eger et al (2004) used a hybrid of the FERIC and ISO standards to document LOS around a customized rectangular perimeter using a light filament in the operator’s seat to represent the eye position of a 170-centimeter, 65-kilogram person and a mirror-mounted measuring device. Based on results obtained around the rectangular perimeter, researchers extrapolated a line of sight to ground, 1 meter and 1.7 meters above ground in order to create line-of-sight diagrams (Eger et al. 2004). In this manner, both visibility impairments and complete blind spots were plotted around the vehicle (Figure 2).

A variation on LOS evaluation was developed for shuttle cars and involves representing the visual requirements for operators using Visual Attention Locators (VALs). These positions were specified from known fore-aft, side-side lateral and up-down height reference locations on the machine (Sanders and Kelley, 1981), and divided into priority one VALs (n=70) that included points that had to be observed by the operator to provide information on the position of the machine in the roadway, location of obstacles and hazards and position of vehicle relative to roof bolts during tramming, loading and dumping. Additional priority two, three and four points (n=24) related to less critical aspects of operating shuttle cars and could be associated with some degree of neck or trunk deviation. Human factors research completed on underground mobile mining equipment by the Pittsburgh Research Laboratory used 54 specific VALs identified for shuttle cars that represented 95% of all visual features necessary for operation (Sanders and Kelley, 1981).

A discussion on the limiting aspects of these various methods is warranted. It is largely inappropriate to use the ISO or SAE standards for evaluation of underground mobile equipment because the acceptable width of maskings has not been specifically defined for underground mining machinery (ie. LHDs, haul trucks). The greatest limitation of the other field line-of-sight methods was the time required to produce one analysis. The adapted FERIC method required three hours of onsite measuring time, in addition to lab calculation time to produce the plots for each vehicle (Eger et al, 1999).

The results did not specifically identify what pieces of the machine were causing the restriction, and did not facilitate design recommendations. Limitations exist for the use of VALs to determine operator visibility. The VAL system also lacked robustness since it was difficult to identify or judge which locations were crucial for operation, and even more questionable to evaluate a machine based on the ability or inability to see a few locations. There are certain VAL’s that will be impossible to see under the best underground circumstances and a machine may receive an undeserved poor assessment.

For this reason our research team sought a way to predict and accurately model the LOS available to an operator and a reproducible, efficient method to test modifications or design prototypes. Based on this, a computer simulation method was developed in a specialized program, and subsequently validated.
against a laser scanner method (Bhatthacherya et al. 2006) with results shown in Figure 3.

Figure 3 The LOS Boxplot to the left was generated using the laser scan (LS) method to evaluate operator sight lines. The blue areas represent sight lines that are visible to the LHD vehicle operator. The checked areas represent space where sight lines are not visible. The LOS Boxplot to the right was created using the Computer Simulation (CS) method. The green areas represent sight lines that are visible to the LHD vehicle operator. The red areas represent space where the operator has no visibility.

Our research group chose the software known as Classic JACK as the optimal tool for conducting LOS computer analysis, because of its ability to position human avatars in the seated driving position of a machine, in addition to several eye view and visibility functions that were built in to the available Task Analysis Toolkit (TAT). Specifically, the coverage plane tool in Classic JACK was used to generate red and green plots as observed in Figure 3. Coverage planes are flat surfaces that can be scaled to any size and oriented in any direction in the environment. The basis of the visibility analysis is that a line is placed at the eye point of the virtual operator and extended to each nodal point on the coverage planes. The number of nodal points can be specified by the user for more or less resolution where a very high resolution results in a solid appearance. When the hypothetical line between the eyepoint and a nodal point does not intersect any part of the vehicle, a clear LOS exists and the nodal point is represented in green. If the line intersects the vehicle before it reaches the intended nodal point, there is no LOS exists and the nodal point is represented in red.

Based on industry feedback, the initial approach for computer LOS analysis was done on a series of connected coverage planes that created a boxplot shape of customizable size (Eger et al. 2010). The boxplot approach was then expanded to a more standardized computer line of sight evaluation (CLOSE) depicted in Figure 4, which includes relevant planes situated at positions like the necessary stopping distance (West et al. 2005). Percentage of available LOS for each coverage plane is also provided by the program as a quantitative assessment. The various boxplots methods have been used to evaluate potential design modifications (Godwin et al. 2008), prototype designs (Henry and Godwin, 2010), and most recently, camera systems for navigation purposes (Godwin 2012).

Figure 4: Computer Line of Sight Evaluation (CLOSE) depicts restricted LOS (red) and available LOS (green) on a 1 meter perimeter around the machine, as well as at important stopping distances ahead and behind the operator.

Strategies to improve line-of-sight

Current mobile mining equipment designs have been associated with impaired lines-of-sight, cramped operator’s compartment, and inadequate seat adjustability (Eger et al., 2004; Godwin et al., 2007; Kittusamy and Buchholz, 2004), all of which contribute to the asymmetric seating postures adopted by LHD vehicle operators. This statement is echoed by McPhee (2004) who concluded in her review of the state of ergonomics in mining by saying: “the link between prolonged sitting, poor cab design, and vibration, with back and neck pain is being recognized but has yet to be addressed in any systematic way by the mining industry”. As reviewed earlier, several researchers have studied the components of the machines that result in impaired LOS. Additional work has been done to identify interventions that minimize awkward working postures, as well as maximize LOS.

The benefits of installing a rotating seat were demonstrated as early as 1978 by Bottoms and Barber who reported an 11° decrease in trunk rotation and a 16° decrease in neck rotation, when a 20° swivel seat was installed in a tractor. In 2001, Toren and Oberg confirmed the benefits of a rotating tractor seat by showing a 50 % reduction in extreme trunk twisting during plowing tasks. Rotating seats have also been installed in fork-lifts resulting in more neutral driving postures and reduced postural loading (Taoda et al., 2002). Similarly, operators of forestry and crane machines with rotating compartments had significantly lower mean head rotation angles (7° and 14°
respectively) than when working without rotating operator compartments (22° and 34° respectively) (Eklund et al., 1994).

Based on this past research, Godwin et al. (2007) demonstrated that a 45° seat rotation resulted in a significant reduction in LHD operator neck rotation, trunk rotation, and trunk lateral bend while simultaneously improved line-of-sight to areas in the working environment that were critical for safe operation. Hence, there is an opportunity for mining equipment manufacturers and the mining industry to evaluate the traditional design of LHD vehicles, in order to enable the LHD operator to utilize more neutral working postures. This approach will be even more important with the introduction of Tier IV engines being introduced to meet diesel-emission standards, the anticipated effect being another increase in the size of underground machinery.

Secondary viewing devices implemented elsewhere in industries have not only improved visibility outcomes, but also improved operator posture. Tobisch et al. (2005) reported that using a GPS navigation system with a computer screen during mulching tasks in the forestry industry could reduce operator head rotations by 90%. A rear-view mirror to aid in detecting hazards was able to reduce the number of right and left glances used by a forestry logger (Cloutier, 2002). A virtual study by Godwin and Eger (2009) showed the benefits of adding cameras to LHD vehicles, in order to allow operators to maintain a neutral sitting posture and still see areas of the working environment that were previously not visible when in a neutral sitting posture.

Secondary viewing devices have been recommended to aid operators in spotting dangers around their machine, such as ground hazards, and pedestrians and to improve opposite-side vision, especially when driving into corners (Schutte and Shaba, 2003). In an effort to improve operator LOS, several new technologies have been tested in both surface and underground mining applications.

Ruff (2001) tested a variety of technologies (closed-circuit video cameras, radar or radio-frequency identification (RFID), ultrasonic, infrared or thermal cameras, GPS) on surface haulage trucks and used reliable detection zone, risk of false alarms, coverage area and adjustability, and weather proofing as measures of usefulness for the application. Although they do not come to a consensus on the best available technology, they do document the pros and cons of a variety of systems. The GPS system is not feasible for underground use, and the RFID approach has not been widely accepted due to the need to have all possible objects tagged. Closed circuit television systems (CCTV), including variations with infrared, and thermal imaging options are making their way into mainstream automobile driving, and may represent a realistic approach to solving the LOS restrictions on large, underground machinery.

**Case study - Augmented vision**

This paper will demonstrate the impact that the four-camera PROVIX system has on LOS for a seated operator of a mid-sized, enclosed-cab LHD. The existing LOS for the operator of a machine with a 4.8m³ bucket capacity was depicted in Figure 2. The solid rays extending from the seated position reflect several blind spots caused by the design of the cab posts, and the light brackets situated on the front booms. The research team uses a customized program to plot the available LOS observed in Figure 2 on a field-based laptop so that immediate feedback is available to the camera installer. For comparison, based on field work with an average-sized male operator in the machine seat, a plot can be produced that represents the LOS when moderate amounts of head, neck and trunk movement are used to view the area around the LHD (Figure 5). Although the distance to ground is not altered, several complete blind spots resulting from the cabin posts can be removed from the plot.

The corresponding plot that depicts LOS to a standing pedestrian is also plotted in Figure 6 with a much smaller scale used. The ability to see a standing pedestrian (1.7m tall) is reasonable for this machine: LOS to the front (~5m) and rear (~6m) while the lights produce obstruction to ~12m mark to the right front area, and the air cylinder on the rear obstructs LOS to ~6m to back right corner. Based on the 2D plots generated, the key areas around the machine that were targeted for improved LOS via the four-camera (PROVIX) system were identified. Since the plots were produced while onsite, the research team could consult with the installer to optimize placement and angles used, as well as an experienced underground hardrock miner, who could provide feedback on appropriateness of the chosen locations.

The four camera locations included: Front Camera located under the Cab roof structure pointing forward, Front Right Camera located on the back half of the machine angled outwards to the front right, Rear Camera positioned in the grill on the rear of the machine, and a Back Right Camera located under the step on the front half of the machine pointing to the back right corner of the machine (Figure 7).
Figure 5: LOS plot represents obstructed line of sight to ground level for a seated operator using moderate amounts of head, neck and trunk flexion. Relying on some operator movement reduces the number of blind spots resulting from the cab posts. Scale in meters.

Figure 6: The green area represents the obstructed LOS to a standing pedestrian (1.7m) tall from the operator’s seated position when using moderate amounts of head, neck and trunk movement. Scale in meters.

The cameras were temporarily mounted in these locations, allowing the research team to perform a second assessment on the rectangular perimeter, from the perspective of each camera. The LOS results using the PROVIX Camera System in conjunction with best operator LOS for the rectangular perimeter are plotted in Figure 8. When comparing to the plot in Figure 5, it is evident that the PROVIX Camera System eliminates all blind spots with the exception of the area directly behind the operator. The projected LOS to ground level has been nearly eliminated, with the exception of three areas: directly in front of the machine is still obstructed since the Front Camera attached to the cab cannot provide complete LOS over the bucket and front half of the machine; the area to the back right because the Back Right Camera was positioned under the step for protective purposes but the step is recessed from the body of the machine; and the area directly across from the operator on the right side, which can be eliminated with optimal angling of the Front Right Camera.

A more realistic scenario was also evaluated for LOS, in which the bucket was rolled back into the empty tramming position. The results are depicted in Figure 9. The Front Camera and Front Right Camera reduced the obstructed area to ground level directly in front of the machine, although substantial blockages still exist out as far as 35-45m in front of the LHD. However, when evaluating obstruction to a standing pedestrian (1.7m), Figure 10 demonstrates (on the same scale used in Figure 9) that the PROVIX Camera System in combination with moderate head, neck and trunk movement essentially provides a 360° view around the machine to a standing pedestrian height.
Summary

Over the last three decades mining methods have moved towards mechanization and automation, which has increased mobile equipment operation underground. With more mobile equipment underground, LOS from the operating compartment has turned into a legitimate safety concern. It will continue to be a concern as manufacturers increase the size of the machines operating in small, narrow passages. The inability of the mobile equipment operator to clearly see pedestrians, objects, or hazards around the machine has contributed to a number of accidents resulting in equipment damage, lost work time, and fatal injury. In an effort to prevent future accidents related to poor LOS, researchers have utilized a number of methods to evaluate operator LOS during mobile equipment operation. The computer simulation methods presented in this case study provide a compelling way to analyze LOS on existing or prototype machines. Until a convincing redesign addresses the severe LOS issues that exist, a reasonable way to improve the operator’s view around the LHD may be through the use of camera systems, as demonstrated in this paper.

Acknowledgements

The LOS research team of the Center for Research in Occupational Safety and Health wishes to thank the mining industry for their ongoing interest and support, and Winsted Group Inc. for their partnership with respect to testing the PROVIX camera system.

References


Bottoms, D., and Barber, T. 1978. A swivelling seat to improve the tractor driver’s posture. Applied Ergonomics, 9,77-84.


