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ADVANCING STRATEGIES TO REDUCE WORKER INJURY RISK ON MOBILE MINING EQUIPMENT

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ABSTRACT

Improving mine worker safety and health is a key goal for the Pittsburgh Mining Research Division of the National Institute for Occupational Safety and Health (NIOSH). Opportunities to enhance the safety and health of mobile mining equipment operators through strategies to lower the risk of musculoskeletal disorders and traumatic injuries is an important element of the overall NIOSH mining research program. This paper reviews various emerging technologies that, if fully developed and implemented, could positively impact the health and safety of mine workers who operate mobile mining equipment. Those technologies showing potential for enhancing operator safety and health in the near future are addressed herein.

Keywords: Mining, mobile equipment, injury risk, collision warning, vibration, seating, ingress/egress.

1. INTRODUCTION

Mining is considered one of the most hazardous industries in the world today. Operating mobile mining equipment is associated with a significant number of fatal and nonfatal accidents each year [1, 2, 3]. Among the issues that can impact the safety and health of mobile equipment operators are exposure to vibration; collisions with other equipment, rocks, other mined materials, objects, and structures; and slip, trip, and fall hazards, particularly related to ingress/egress systems. For many of these hazards, equipment modifications and advanced vehicle monitoring technologies have the potential to prevent or significantly reduce the hazardous effects. Examples of these modifications and technologies are discussed in the sections that follow.

2. VIBRATION MONITORING TECHNOLOGY

The Mine Safety and Health Administration (MSHA) receives and stores injury statistics for the mining industry. These statistics demonstrate the need for monitoring and mitigating whole body vibration (WBV) hazards for mine workers. For the period 2012–2016, surface mines and quarries reported a total of 523 nonfatal injuries with days lost (NFDL) and no days lost (NDL) related to the back, neck, and head in the surface metal, nonmetal, stone, and sand & gravel industries. These included cases with accident types of struck against a stationary object and struck against a moving object. Eighty-three percent (434) of these accidents were NFDL. Metal operations reported the highest percentage of NFDL at 39.8% of the total 523; stone operations reported the second highest percentage of NFDL at 35.2%, and sand & gravel came in third with 13.6% NFDL injuries. Haul trucks, front-end wheel loaders, and bulldozers show the highest number of injuries related to jarring/jolting and WBV with 330, 129, and 39 injuries, respectively. The body part most affected relative to these injuries was the back (426) and secondarily the neck (88). These injuries can be characterized generally as strains. Typically, incidents of jarring/jolting were caused by running over rocks, ruts, or potholes, running into other mobile machinery or equipment, being struck by other operator-driven machinery, and equipment rollovers [4].

Operators of mobile mining equipment are afflicted by a high prevalence of musculoskeletal disorders (MSDs), likely caused by exposure to WBV [5]. Previous research has shown that mobile equipment operators are prone to hazardous levels of WBV exposure from equipment, including haul trucks, bulldozers, and front-end loaders [6]. Extensive reviews of the epidemiological literature documents a significantly increased risk in spinal and peripheral nervous system injuries after intense, long-term WBV exposure, as well as an increased health risk in the vestibular system, digestive system, peripheral veins,

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and internal organs [7]. Spinal injuries associated with WBV exposure, including lower back pain (LBP), are mainly dependent on the magnitude of acceleration, exposure duration, and operator posture [8, 9]. For safety and health professionals in the industry, the ability to quickly monitor the magnitude of acceleration and excitation duration that each operator is subjected to by their equipment can have a significant impact on worker health.

Harsh conditions, heavy use, and cramped layouts of mobile equipment cabs are significant difficulties that stand as a barrier to monitoring WBV exposure. Currently, monitoring WBV exposure is typically conducted ad hoc with instrumentation such as tri-axial accelerometers placed on the seat, frame, and steering components, and a data acquisition system placed in the cab. The task of affixing sensors, installing data acquisition systems, explaining the process to operators, and fielding questions from the operator not only interrupts worker productivity, but only yields a onetime measure of WBV. An expandable, multi-channel acquisition system with accelerometers, load cells, and force plates pre-installed by the manufacturer at key locations—such as the seat, steering components, shock absorbers, and other locations—has the potential for monitoring WBV easily, as well as calculating transmissibility, driving point mechanical impedance, absorbed power, and seat-to-head transmissibility (STHT) [10].

3. SEAT TECHNOLOGIES

The challenge with utilizing a suspension seat is that it will amplify vibration when traveling over small perturbations in a roadway surface at moderate to high speeds [11]. Figure 1 shows a comparison of seat types and seat suspensions technology for an approximately 60-yr period. In using just foam padding in the seat with no suspension, researchers reported in a study of WBV exposure with metropolitan bus drivers that just under 90% of the Z-axis (vertical) vibration was transmitted to the driver for nearly 70% of the exposure time period [12].

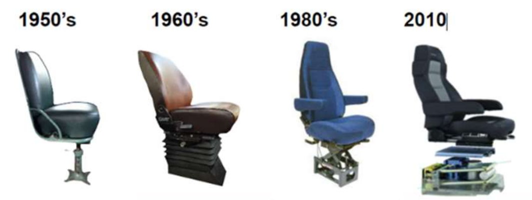
Similarly, tests have been conducted on a simple air bladder cushion system that included a seat pad and a seat back pad with no other suspension system. The results showed that the air bladder system in the absence of any other suspension system reduced the Z-axis transmitted vibration to the operator to a level of 67% for over 60% of the exposure time [11].

To address the issues with an air-ride seat, a new active suspension seat has become available. The features of the active suspension seat include [11]:

- Air suspension system like a conventional air-ride truck seat.
- A microprocessing sensor in the seat base that processes seat sensor data in order to cancel forces in real time.
- A linear electromagnetic actuator that counteracts forces.

The University of Washington has tested suspension seat technology with a group of 16 truck drivers. The findings of their study showed that the passive seat suspension system transmitted 95% of the Z-axis vibration to the operator for more than 60% of the time interval. In contrast, the active seat suspension limited the transmission of Z-axis vibration to the operator to a level of 36% for more than 80% of the exposure time interval [11].

Comparison of Seat Suspension Technologies



	Static	Mechanical Suspension	Air-Ride	ElectroMech Active
Uses	On-Road	On/Off Road	Many	Trucking
Cost	Low	+ Moderate	++ Moderate	+High
Pros	+++ WBV Not Weight Dependent	++ WBV	+++ WBV Less Weight Dependent	WBV?
Cons	Bumps	Weight Dependent Amplify WBV	Amplify WBV	Currently On-Road

FIGURE 1: SUSPENSION SEAT AND SEAT TECHNOLOGY COMPARED OVER A 60-YR PERIOD. PLUS SIGNS INDICATE FAIR (+), GOOD (++), BETTER (+++), AND QUESTION MARK (?) UNSETTLED [11].

4. COLLISION WARNING TECHNOLOGY

Mobile equipment at surface mining sites injure and kill mine workers each year. An analysis of the 133 haul truck-related fatalities occurring at U.S. mine sites from 1995 through 2010 determined patterns in these fatalities [3]. Loss of control, ground fails, and two-vehicle collisions were the primary causes of fatalities to drivers, whereas unexpected movement, falls from vehicles, and hit by other vehicles were the primary causes of fatalities to nondrivers. Collisions were found to result in fatal injuries to operators as well as passengers. Recently, there has been an increase in the number of mobile equipment collisions resulting in fatalities at surface mining facilities with 40% of all mining fatalities and 30% of all nonfatal injuries sustained in 2017 involving mobile equipment. In 2018, the Mine Safety and Health Administration began a Powered Haulage Safety Initiative that includes mobile equipment as well as conveyor safety. One of the targeted areas is large vehicles striking smaller vehicles.

The large scale of mobile mining equipment and the location of the operator's compartment create significant, unique blind areas that have contributed to vision-related issues such as collisions, striking mine workers, and backing over unseen edges [13, 14, 15]. Video cameras are used extensively on surface haulage equipment but have significant limitations when compared to other types of technology [14]. Large surface haulage equipment would require more than one camera to cover the blind areas [16]. Actively monitoring displays from several cameras, along with the displays of existing data sources such as dispatch and maintenance information, can create human factors concerns and increase operator workload. Moreover, the issues associated with maneuverability and response time due to the momentum of the vehicle may reduce the ability of video cameras to prevent all collisions [15]. Advanced technologies, such as collision warning and collision avoidance systems, have the potential to actively monitor these blind areas for the presence of nearby mine workers, vehicles, structures, and equipment and prevent a collision by slowing or stopping the equipment.

Collision warning systems utilize position tracking and communication systems to determine the relative locations of objects, personnel, and equipment. Collision warning systems are not new to mining and are required for use on place-changing continuous mining machines in U.S. underground coal mines (30 CFR§75.1732, March 2015) [17]. In surface haulage, these systems are not required and are, therefore, not as widely used. There are three MSHA-approved proximity detection systems for use in underground coal mines and several commercially available collision warning systems (which have not been evaluated or approved by MSHA) for surface haulage equipment. Several studies have examined collision warning systems under development for surface haulage equipment [18, 19, 20, 21].

Past NIOSH research has addressed the early examination of collision/proximity warning systems and determined that many systems were effective in detecting workers, vehicles, equipment, and other objects in the blind areas of surface mobile mining equipment [16]. Recommendations included the integration of two or more technologies in order to provide redundancy, support close-in detection at low speeds and long-range detection at higher speeds, allow operators to verify the presence and location of identified obstacles, provide road edge detection, and decrease nuisance and false alarms. Nuisance and false alarms would be a significant risk for collision warning systems that are tied into collision avoidance systems. If frequent false alarms cause the braking or stopping of equipment, this would create new risks and decrease operator acceptance of the system. Another recommendation addressed brakes that are not automatically activated and collision warning systems that act solely to increase situational awareness, allowing the operator and nearby workers to take action to avoid collisions [16]. Given that this earlier work is more than a decade old, NIOSH has initiated a new pilot study that is focusing on identifying and characterizing health and safety issues of haul trucks by systematically evaluating accidents/injuries, equipment operator perspectives, and suitable interventions.

5. ENHANCED INGRESS/EGRESS SYSTEMS

Although large strides have been made in autonomous mobile equipment outside of the United States, most mobile equipment still needs operators to have partial or full control of the equipment. Having an operator in the equipment predicates the need for an operator's cab and an access system to get to the cab. Ingress (getting on) and egress (getting off of) large mobile equipment, such as front-end wheel loaders, wheel dozers, and haul trucks, often involves the use of some combination of steps, ladders, and platforms. From as early as 1980, research has been conducted to improve access to tractor cabs and mobile equipment [22, 23], evaluate step and handhold dimensions on semi-trucks and agricultural equipment [24], study the design of steps and stairs to access utility trucks [25], measure ground reaction forces and estimate slip potential when exiting commercial tractors, trailers, and trucks [26, 27], and evaluate different descent techniques from truck cabs [26]. Similar research for mobile mining equipment trucks, such as haul trucks, was also conducted around 1980 to improve the design of ingress and egress systems [29, 30]. However, since then, original equipment manufacturers have not significantly changed the ingress/egress systems provided on large mining equipment. Additionally, most research studies have only investigated the causes of injuries and highlighted the hazard posed by ingress and egress and have not included an evaluation of improved or redesigned systems [1, 2, 3, 31].

Issues associated with large mobile mining equipment are often related to the use of ladders or the high first steps/rungs [29, 30, 31]. Although one study found no difference in the potential fall severity when ascending or descending ladders [32], the prevalence of nonfatal incidents occurring during egress were a lot higher than during ingress when investigating front-end wheel loaders [31]. Prior studies have focused investigations on multiple aspects of ladder ascent and descent [33, 34, 35, 36]. The need to use the hands to help stabilize the body and the potential to slip off of the rungs [37, 38, 39, 40] are the two main reasons that place ladders at a significant disadvantage to stairs. Jumping from mobile equipment also results in higher ground reaction forces that can increase injury risks [23, 25].

Recommendations to replace the ladders on large mobile mining equipment with stairs or inclined ladders are not novel [27], and a web search of available solutions yields no less than five readily available solutions from companies such as B&D Manufacturing, Safe Boarder, ISS Solutions , Australian Diversified Engineering, and Power Step Inc. Some recommendations for enhanced ingress/egress systems go as far as attempting to eliminate the need to use the ingress/egress system on the equipment and replacing it with a fixed access system that allows access to the cab directly, allowing for a potentially safer alternative [31, 41].

Research [31] indicates that contaminants on the ingress/egress system pose a slip and fall hazard. Current practice and solutions only allow contaminants to be cleaned off the ingress/egress system prior to boarding. During descent, there is no way to clean contaminants such as mud, water, and material that may have accumulated when operating the equipment. Future ingress/egress systems should have a way to prevent the accumulation of such contaminants or provide a means to clean them prior to descent from the equipment.

5.1 Lighting improvements

Finally, a recent investigation of illumination measurements taken about 38 pieces of mobile mining equipment identified average light levels as 2.91 lux at the ground below the first step/rung, 0.26 lux at the first step/rung, and 2.64 lux at the platform(s) above the top ladder rung leading directly to the operator’s cab when supplemental lighting was absent during pre-dawn hours. Conversely, light levels of 8.02, 11.5, and 23.1 lux, respectively, were measured when supplemental lighting was present. The Illuminating Engineering Society recommends 100-200 lux in areas where tasks are occasionally performed, including stairways. The overall lack of illumination can be attributed to the location of the luminaires and the light output. In addition, the lower values at the ground and first step were attributed to the location of the luminaires on the equipment, where the equipment itself cast shadows on the ground below steps/rungs and onto the first few steps/rungs. Illumination on the ingress/egress systems is essential for hazard recognition and hazard identification and needs to be improved. Improvements to the luminaires, such as the use of light-emitting diodes (which are shown to improve hazard detection [42, 43, 44]), and placement of luminaires, so they provide adequate illumination on key components such as the ingress/egress system, should be made on mobile mining equipment to reduce the risk associated with ingress/egress and improve worker safety.

6. FATIGUE MONITORING

Managing fatigue has led to various technologies that may be useful in preventing injuries and fatalities with mobile mining equipment. The monotonous nature associated with operating mobile equipment leaves mine workers vulnerable to fatigue [45]. Consequently, mining companies are recognizing that fatigue management is a key component to ensuring safe mining operations [46]. Lack of sleep is recognized as the number one cause of fatigue. Although the risk of operator fatigue or drowsiness may occur at any time during a shift, the tendency is for most incidents of fatigue to manifest during lows of the circadian rhythm (biological clock) [47]. Past research [48, 49] has noted that sleep loss as little as 2 to 3 hours per night can impact sleepiness across days.

Fatigue management technologies may be generally described as predictive and reactive. Reactive technology would detect fatigue after the operator may already be falling asleep. Predictive technology, in contrast, would detect fatigue when the operator is beginning to show signs of it, which can manage operator risk in a proactive way. There are several commercially available predictive and reactive fatigue management technologies. These include: Predictive: Circadian and Fatigue Management and Modular Mining Systems; Reactive: Smart Cap and Fatigue Science – Readiband [46]. The success of these systems for preventing fatigue-related injuries in mining has yet to be examined.

7. CONCLUSIONS

The operation of mobile mining equipment imposes significant risks to operators and other workers due to issues associated with exposure to WBV, inadequate ingress/egress, insufficient lighting, and the potential for collisions. The design of the ingress/egress systems must be improved to help prevent slips and falls. The use of LED luminaires placed appropriately to provide sufficient illumination on key components of the ingress/egress systems should also be implemented. Advanced vehicle technologies show potential to combat many of the other risks and improve the situational awareness of the mobile equipment operators. Many of these technologies are available as stand-alone systems and further developments should be made to ensure the seamless integration of these systems. Adding additional functionality to existing systems may increase their proliferation in the mining industry.

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