Operating speed assessments of underground mining equipment

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Abstract

Numerous fatal/nonfatal accidents involving underground workers struck by powered machinery occur yearly, with continuous miners and roof bolters involved in the majority of these accidents. In an attempt to reduce these accidents, researchers at the the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory conducted studies of operator interactions with the motions of continuous mining machines and roof bolter boom arms. These operators generally perform their tasks in close proximity to the equipment in confined workspaces, often employing awkward postures. Since experiments with human subjects using the actual equipment were not feasible due to safety concerns, researchers opted to conduct controlled experiments in laboratory settings. Utilizing motion capture technologies and computer simulations, the studies collected data on equipment and operator movement in a range of seam heights and working postures. This article details the results of these studies to examine operating speeds based on usage and seam height.

Introduction

The U.S. Mine Safety and Health Administration (MSHA) reports that both fatal and nonfatal remote-control continuous miner accidents from 1999 to 2007 averaged 243 per year during routine mining activities, with the majority of accident victims working within the turning radius of moving continuous miners. The mining industry uses an educational aid called "red zones are no zones" (MSHA 2006) to help operators of continuous miners to understand which areas around the machine to avoid. However, fatalities and injuries continue to occur.

During the same period, MSHA data shows an average of nearly 600 accidents per year related to roof bolting, accounting for nearly one-third of powered machinery accidents. There are currently no regulations or data on determining safe velocities for roof bolter boom arms operating in close proximity to workers in underground mines (MSHA, 1994 and Turin et al., 1995).

Other industries, such as robotics, have conducted studies and implemented guidelines for safe machine velocities. The U.S. Department of Occupational Safety and Health Administration (OSHA, 1987) and the U.S. Department of Energy (DOE, 1998) recommend velocities be limited as low as 152 mm/sec (6 in./sec) for manufacturing robots during programming. Another study, (Etherton, 1987), recommends 254 mm/sec (10 in./sec) as a safe velocity for robots operating in proximity to humans.

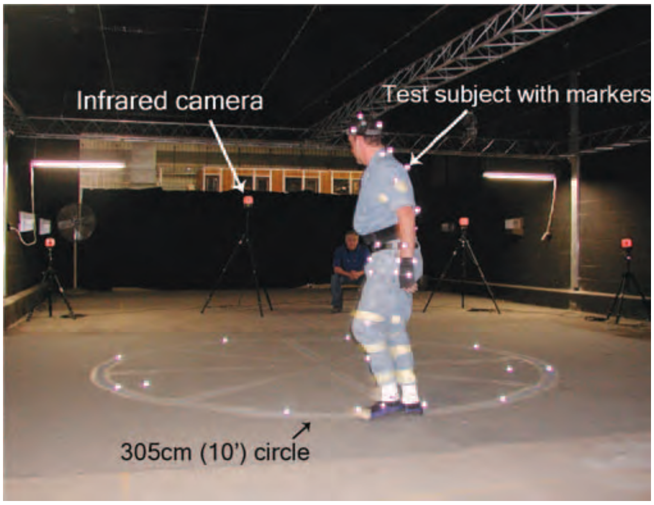
To address these issues, the National Institute for Occupational Safety and Health (NIOSH) conducted studies to investigate safe operating speeds for these two machines. To minimize risk to the human subjects, the studies used motion capture technologies and computer simulations in a controlled laboratory setting.

For the continuous mining machine study, the researchers attempted to determine how quickly subjects could escape from the perceived danger of a machine rotating towards them. Continuous mining machines move in a straight line relatively slowly, but their rotational speed can be appreciably faster when the tracks move in opposite directions. In that case, the machine pivots around the center point of its tracks. The front and back of the machine are far enough from this center to result in high velocities in the turning direction. Researchers conducted numerous motion capture sessions with human subjects in controlled laboratory environments. This data was used to create a virtual environment to analyze factors influencing struck-by accidents during the tramming of a continuous mining machine.

The roof bolter boom arm motion studies had United Mine Workers of America (UMWA) volunteers operate a model of a Fletcher Ranger II left-hand roof bolter arm while recording the motions of the bolter boom arm and subjects. While this manufacturer has the majority of the underground roof bolter market, the use of this particular manufacturer's design should not limit the application of the results of these studies because other manufacturers' articulating boom arms use similar designs. NIOSH's model is of the common 1,830 mm (72 in.) length arm and all testing was done with full sump extension. For the vertical boom speed research, a virtual environment with digital humans was created to run simulations. A level of randomness added to the motion of the digital operator during the drilling and bolting cycle enabled the simulation to realistically

FIGURE 1

Motion capture for continuous miner speed study.



represent the operator's motions while performing the bolting task. Volberg and Ambrose (2002) discuss in detail the development of these random motions. The simulator output produced data on the number of contacts between the operator and moving boom arm. This data was analyzed to show the effects of vertical speed on the risk of boom arm contact with the operator. For the horizontal boom speed study, it was only necessary to complete analysis of motion capture data from the human subjects testing to determine if an operator's safety could be compromised by excessive speeds.

Procedures

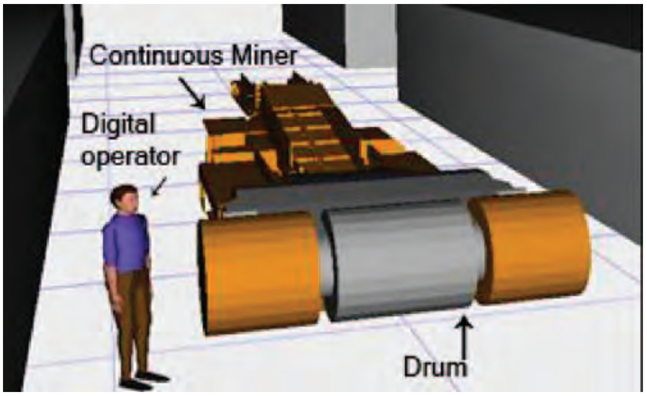
The continuous mining machine investigation analyzed factors influencing struck-by accidents during tramming by using a digital human model (DHM) with simulations driven by captured human motion data with a variety of subjects, postures, facing orientations, environmental constraints and machine characteristics. The DHM used MSHA fatality information to validate the model parameters relating to operator position, which could pose a threat to operator safety. Some of these positions were in the MSHA red zone (MSHA, 2006). It should be noted that the results from this study make a case supporting or even expanding the red zone strategy.

The human subjects recruited from local mines were asked to perform realistic movements in a laboratory setting (Fig. 1) that mimic escaping from the path of a moving machine. The motion data was obtained using various operator work postures and escape paths (directions) typical for tramming operations of continuous miners. Complete details of these tests, the development of the DHM and data analysis are contained in Bartels et al. (2008).

The DHM, shown in Fig. 2, was developed using the motion capture data to provide the means to measure parameters that would be used to predict struck-by events when the operator tries to move out of the way of the moving machine. The digital human operator's movements were constrained by using motion capture data of test subjects as discussed in (Bartels et al., 2007). To present a realistic operator response to the moving machine, researchers programmed the operator's movement using a delayed start in accordance with reaction times reported by Drowatzky (1981). This delay ranged from 0.19 to 24 seconds. The DHM output parameters included:

FIGURE 2

Digital human/continuous mining machine model.



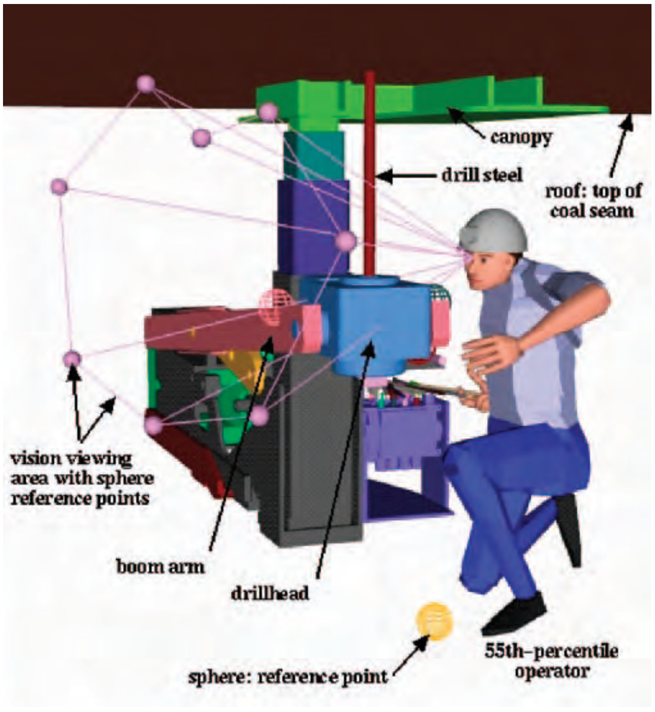
- The time when the machine first begins to move.
- The time when the operator first begins to move.
- The time when the operator is struck by an object.
- Name of the object that struck the operator.
- The operator's distance from the start position when struck by an object.

MSHA's fatality reports (Dransite and Huntley, 2005) provided information to help validate the model regarding objects that struck the operator and the operator's distance and location from the machine at the time of being struck.

A similar method was used to investigate the vertical

FIGURE 3

Digital human/roof bolter model.



speed for the roof bolter arm.

Researchers developed a three-dimensional computer model that uses virtual human simulation software as the primary means to gather contact data when the boom arm touches the operator's hand, arm, head or leg. Human subject tests using UMWA volunteers with a full-scale working mockup of a boom arm were used to collect motion data that helped determine parameters for building this model. The computer model, shown in Fig. 3, contains a virtual mine environment that includes a roof bolter boom arm and a virtual human operator. The complete development of this model and data analysis is available in (Ambrose et al., 2005).

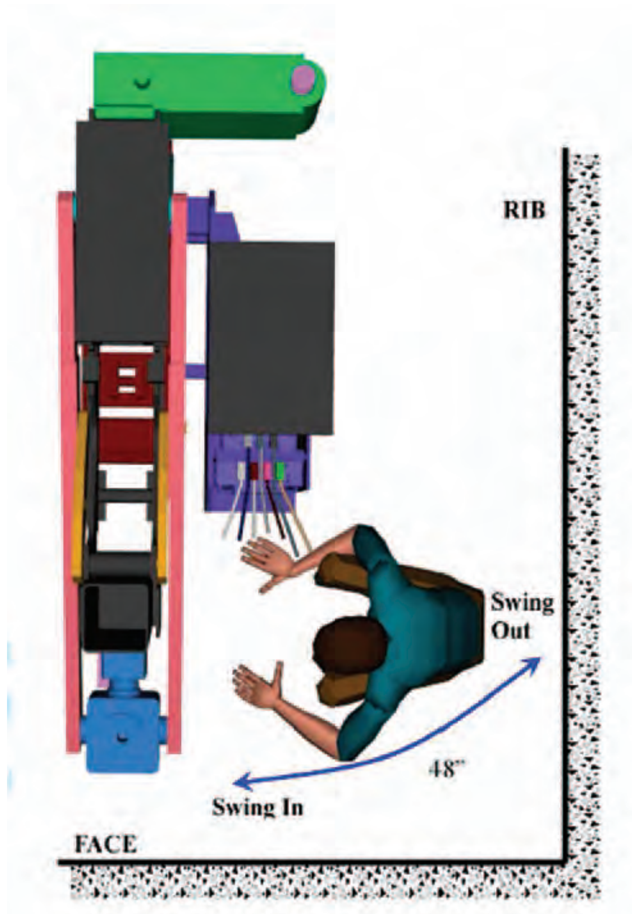
The study of the horizontal speed of roof bolter boom motion examined the relationship between operator and boom arm motion, with the goal of increasing the safety of bolting machine operators during lateral boom (swing) operations. Swing motion usually occurs when the operator is repositioning the boom arm to a new bolt insertion location; this action requires that the operator properly actuate the correct control(s) and simultaneously reposition his/her body in coordination with the moving boom arm. Figure 4 depicts the motion of an operator during a boom swing. In low seam heights, operators may perform this task from kneeling positions, which further hinders their ability to keep pace with the boom arm. The fundamental issue is that it is not known what boom swing velocities will minimize the operators' risk of injury while still allowing the operators to perform bolting functions effectively. Roof bolter manufacturers set the rate of boom swing to a known velocity, but these settings may subsequently change from repair or rebuild.

With the 1,830 mm (72 in.) bolter arm mock-up at full sump extension, the operator's station moves about 1,220 mm (48 in.) during a full swing. This mock-up bolter arm has adjustable operating speeds and various safety features to minimize risk to test subjects. The operator control layout used in the mock-up (Fig. 4) is a layout that is representative of older units used in the field. Several versions of controls are in use because manufacturers alter machines to meet their customers' needs. Figure 5 shows a subject at the start of a test in the kneeling posture.

The tests used velocities of 300, 410 and 610 mm/sec (12, 16 and 24 in./sec) when moving away from the operator (swing-in) and 300, 350 and 410 mm/sec (12, 13.7 and 16 in./sec) when moving toward the operator (swing-out). The lowest velocities for both directions of boom arm testing were the manufacturer's base velocity. The fast velocities were arrived at through preliminary testing using NIOSH test subjects. Kwitowski and Ducarme (2007) provide complete descriptions, data analysis and details on these tests. The medium velocities used were calculated to be half way between the fast and slow velocities selected. Since the radius of the motion is preset, all velocities were converted to a time base for full swing travel. The times for full swing and velocities that were used are listed in Table 1. Both actual and target times and velocities are listed in the table because the method used to set the velocities did not result in the exact target swing times. The actual swing times achieved were used in the analysis process to ensure accuracy. A small PVC tube attached to the boom arm simulated the obstruction created by the actual roof bolting machine's protective canopy and was adjusted appropriately for each test to correspond with the seam heights used. The sequence of velocities, seam heights and posture combinations were randomized. Several markers were placed on the boom arm to record its motion in addition to the standard marker set on the subject.

FIGURE 4

Operator movement during boom swing.



Results

The studies, as expected, show that speed had an impact on the possibility of worker injury. In addition,

Table 1

Times and velocities used for UMWA trials.

	Swing-in		Swing-out	
	Target	**Actual (avg.)**	**Target**	**Actual (avg.)**
Normal				
Time, sec.	4.0	3.7	4.0	3.8
Velocity, cm/sec	30.5	33.0	30.5	32.1
Medium				
Time, sec	3.0	2.7	3.5	3.2
Velocity, cm/sec	40.6	45.2	34.8	38.1
Fast				
Time, sec	2.0	2.2	3.0	2.7
Velocity, cm/sec	61.0	55.4	40.6	45.2

FIGURE 5

UMWA subjet kneeling posture.

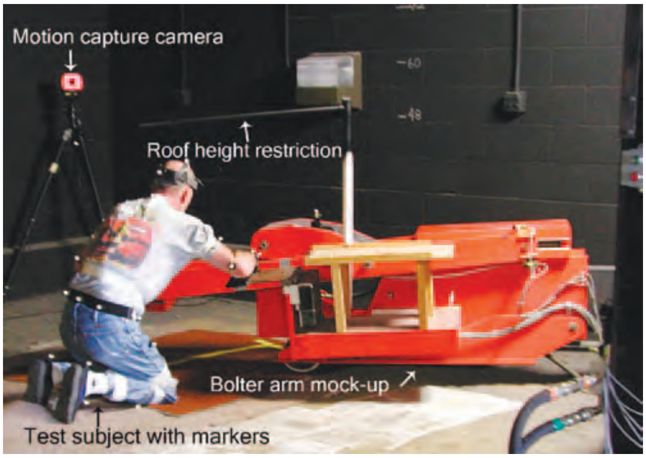
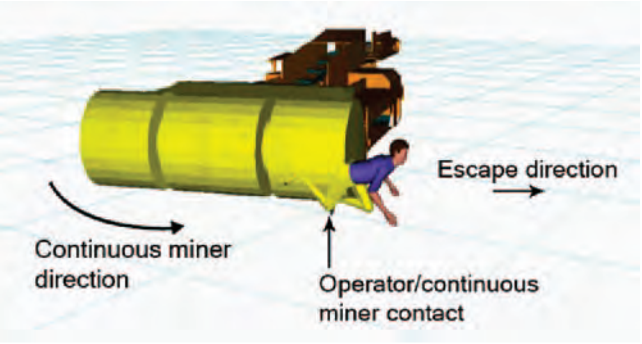


FIGURE 6

Simulation showing operator struck by machine.



operator posture and position were factors in the frequency of struck-by events in the studies. Since the studies involved a complex relationship between the influential factors, seam height and proximity to the machine could affect the frequency of struck-by events and the significance of the other variables.

For the evaluation of continuous miner speeds, frequency and cross-tabulation analyses were completed on 14,308 simulations. Of these, 10,254 exhibited struck-by events between the operator and the continuous miner equipment. Figure 6 shows the simulation at the instant a struck-by event occurs. Cross tabulations showed that two major factors had an effect on the operator's ability to avoid being struck by the machine: the speed of the machine and the operator's distance from the machine. The effect of the operator's distance from the machine can be seen in Fig. 7. The differences in incident rates between a distance of 300 mm (1 ft) and 610 mm (2 ft) is small but, at 910 mm (3 ft), the incident rate is significantly reduced. Figure 8 shows the effect of machine rotational speed on struck-by events. Both figures show an almost linear reduction in struck-by rates as machine speed is reduced or operator distance is increased. These results are not surprising but do indicate that recommendations on speed and operator distance from the machine could reduce operator injuries. What did stand out was that there were no rotational speeds that showed a dramatic reduction in incidents. A maximum reduction of 20% occurred between the maximum and minimum speeds. Position, on the other hand, showed a sudden 40% decrease in incidents at the 910 mm (3 ft) distance compared to the 610 mm (2 ft) distance. This would indicate that position may be the most significant parameter in preventing accidents.

Additional data was collected from the simulations such as the parts of the body most frequently struck (Fig. 9). Upper body parts tend to be struck most often due to the shape of the mining machine, particularly the tail, that can only contact the operator's upper body. This also explains why stature did not have a significant influence on incidents.

The simulation results for roof bolter boom vertical speed were evaluated using frequency distribution, cross-tabulation and survival analyses. These analyses were conducted using only the occurrences for the operator with slow reactions that included one contact per simulation execution. The difference between slow and fast reaction times of the operator did not significantly affect the outcome because the number of contact incidents between slow and fast reaction times was less than 1%.

Results from the frequency distribution analysis showed:

FIGURE 7

Effect of operator distance to CM on contacts.

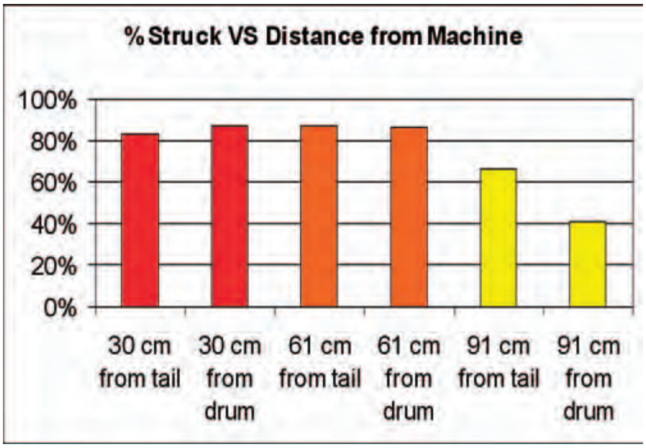
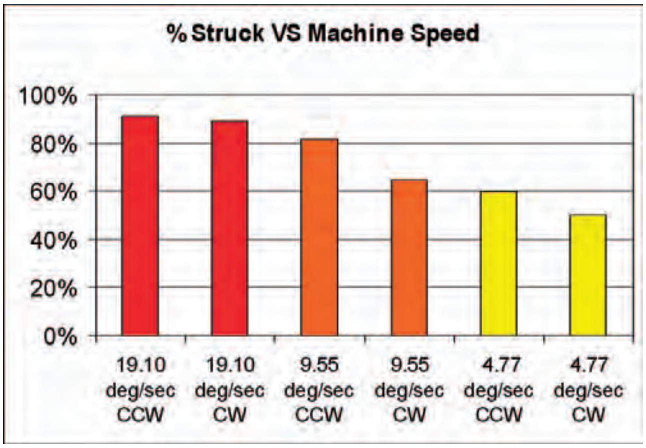


FIGURE 8

Effect of continuous miner speed on contacts.



- The 1,520 mm (60 in.) seam height had 59% of the total number of contacts.
- The combined right and left one knee work posture had 49% of the contact incidents.
- The boom speeds of 41 and 560 mm/sec (160 and 22 in./sec) combined for 43% of the contact incidents (Fig. 10).
- Of the total number of contacts, 76% occurred during boom up motion.

The cross-tabulation analysis had the following results:

- Regardless of boom speed, the boom-up direction had the majority of the contacts, with most occurring at the highest two speeds of 41 cm/sec (16 in./sec) (22%) and at 560 mm/sec (22 in./sec) (21%).
- The both-knees work posture resulted in more contacts than the other postures and had the largest number of contacts (23%) at the boom speed of 410 mm/sec (16 in./sec).
- The machine part that had the most contacts was the boom arm and those contacts occurred during the highest speeds of 410 and 560 mm/sec (16 and 22 in./sec).
- The body part that had the most contacts was the hand, with the largest number of contacts (24%) occurring during the boom speed of 410 cm/sec (16 in./sec).
- The 1,520 mm (60 in.) seam had more contacts than the other seam heights, with most (22%) occurring at the 410 mm/sec (16 in./sec) speed (Fig. 11).

The survival analysis results were:

- Boom speed is the most important factor in determining the chance of an operator making contact.
- Boom speed was the most influential variable for explaining the time to a contact occurring.
- Increases in boom speed resulted in an increased chance of a contact throughout the period of the simulation.
- The chance of being contacted at the two highest boom speeds was generally two to four times greater than at 33 mm/sec (13 in./sec) and four to eight times greater than at 180 mm/sec (10 in./sec).
- A boom speed greater than 410 mm/sec (16 in./sec) resulted in a substantial increase in the chance of a contact, while speeds less than or equal to 330 mm/sec (13 in./sec) had much lower probability of a contact occurring.

Horizontal roof bolter boom swing speed was evaluated based on the difference in operator acceleration and the speed of the approaching bolter boom. Figure 12 shows the results for the 1,830 mm (72 in.) standing posture, which are typical results for all postures except the 1,220 cm (48 in.) kneeling results, which are shown in Fig. 13. The slope values were calculated as the averages of all 12 test subjects. When the value of slope is positive, the subject to boom arm distance was increasing. Conversely, a negative slope indicates the subject to boom arm distance was closing. As the absolute value of a slope increased, the velocity between operator and boom arm also increased.

The swing direction must be taken into account when deciding whether a positive or negative slope is desired. During boom swing-out, the boom is moving towards the operator and a positive slope value indicates the operator is moving faster than the boom. This situation should be a benign case and may indicate boom swing velocity could be increased. However, a negative slope value during boom swing-out indicates the operator to boom arm distance is decreasing, meaning the operator could not keep up with the boom arm motion and a reduction in swing velocity should be considered. This is the more hazardous situation, as the possibility of operator to boom arm contact and exposure to pinch point and crushing hazards increased. The most hazardous situations occur when the slopes are more negative than -0.5 during swing-out. At this slope, the closing velocity between the boom arm and the operator is 50% of the arm's velocity. As the actual fast swing-out velocity was about 440 mm/sec (17.5 in./sec), the closing velocity between operator and boom arm would be about 230 mm/sec (9 in./sec). This velocity exceeds the limiting velocities from Etherton, 1987 and OSHA, 1987.

For boom swing-in events, the boom arm is moving away from the operators, forcing them to follow it. If the boom arm is moving faster than the operator can follow, the distance between the arm and operator will naturally increase. However, this situation could increase tripping hazards.

FIGURE 9

Frequency of continuous miner contact by body part.

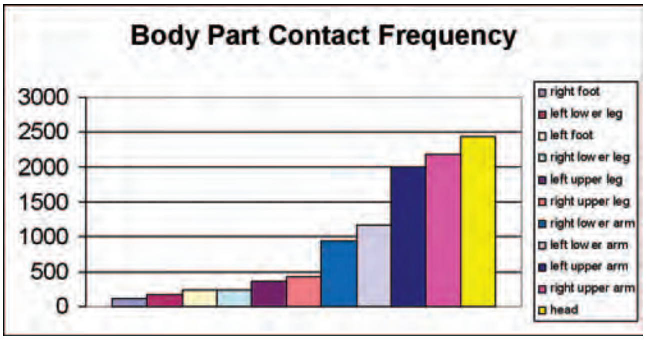


FIGURE 10

Frequency distribution of vertical boom speed incidents.

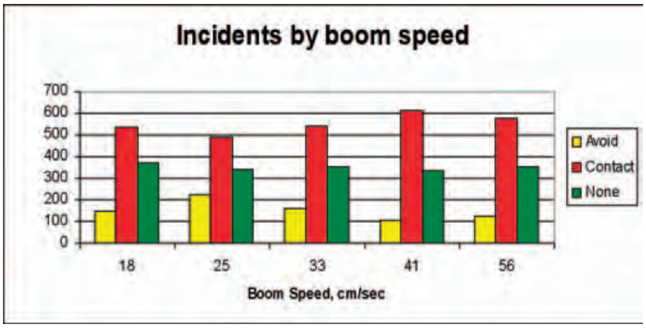


FIGURE 10

Frequency distribution of vertical boom speed incidents.

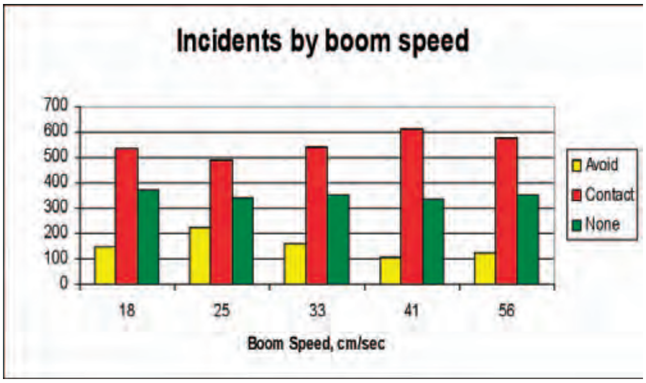


FIGURE 11

Cross tabulation results of vertical boom speed and seam height.

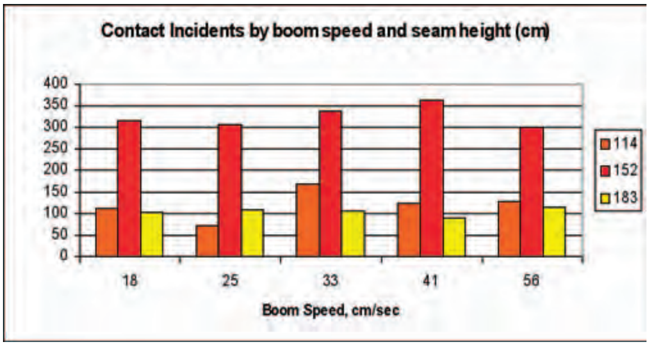


FIGURE 12

1,830 mm (72 in.) standing posture, horizontal boom speed results.

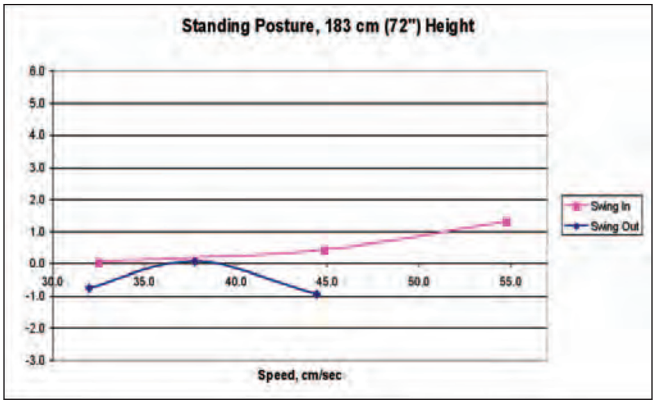
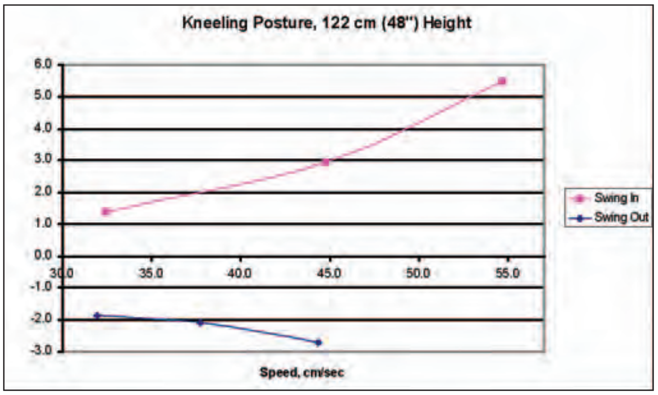


FIGURE 13

1,220 mm (48 in.) kneeling posture, horizontal boom speed results.



For all postures except one, the trend is clear. As the boom swing velocity increased, the velocity of the boom arm approach or recession relative to the operator increased. The kneeling 1,220 mm (48 in.) results show that the slowest velocity tested, ~30 mm/sec (12 in./sec), appears to be excessive for both swing directions, as the operators were unable to keep pace with the moving boom arm. During swing-out motion, the slope value was always negative, meaning the operator to boom arm distance decreased at all velocities.

Conclusions

The data obtained in these three studies revealed a complex interaction of factors that affect the risk of struck-by accidents when miners operate mining machines in an underground mining environment. However, the increased understanding of these relationships should ultimately result in recommendations that reduce the risk of potentially fatal accidents to machine operators.

Continuous miner rotational speed was one the most influential variables in terms of explaining the struck-by event occurring. Increases in machine speed resulted in increased chance of being struck and the increased risk associated with higher speeds was constant throughout the times investigated in the study. In general, compared to the 4.77 deg/s condition, the 9.75 deg/s speed increased risk of being struck by 20%. The distance of the operator from the machine, at the start of the test, also had a significant influence. The relative risk of being struck by the machine, while working within 0.3 m (12 in.), was the greatest at the beginning of the simulation. However, the struck-by incidents drop 40% at an operator position 0.9 m (36 in.) from the machine, indicating position may have a greater influence on incidents than machine speed. It is important that continuous miner operators constantly keep aware of their position in relation to the machine and maintain a safe distance to reduce their risk of being struck.

Data analysis of roof bolter vertical boom speed simulations shows that the speed of the boom arm is the most important factor in determining the risk of an operator making contact with it. Regardless of other variables, contact incidents were always greater when the bolter arm was moving up, greater on the hand and greater for the boom arm part of the machine. The reason why the subject experiences more contacts when the boom arm is moving up rather than down is that more risk occurs during drilling and bolting when the boom arm is ascending. Based on the data collected, boom speeds greater than 330 mm/sec (13 in./sec) result in a substantial increase in risk to the roof bolter operator for making contact. Speeds less than or equal to 330 mm/sec (13 in./sec) are associated with a more modest relative risk of making contact, which represents a decrease in potential hazard.

For all the studies of horizontal roof bolter arm swing, velocity appears to be a primary factor determining operator safety in relation to pinch point and crush hazards during the boom positioning phase of the bolting sequence.

For the tests conducted with the boom swing-out velocity set to the average of 440 mm/sec (17.5 in./sec), the absolute values of slopes were equal to or greater than 0.5 and, therefore, should be considered too fast for all the postures tested. The medium rate tested for swing-out averaged 380 mm/sec (14.9 in./sec) and resulted in satisfactory slope values for all postures tested except for the 1,220 mm (48 in.) kneeling posture.

The results presented indicate that operators should be able to keep pace with the manufacturer's standard boom swing rate of 300 mm/sec (12 in./sec) for all the tested postures except for the 1,220-mm (48-in.) kneeling posture. Additional research needs to be conducted to provide adequate data for setting swing velocity guidelines at the 1,220 mm (48 in.) working height.

The data shows that operators are able to keep pace with horizontal boom swing velocities in excess of the manufacturer's standard in other working heights and working postures. However, caution must be used with utilizing the information obtained from these studies because the test trials were of a limited duration and the subjects were permitted rest periods as needed. Operator fatigue could be a factor associated with higher velocity settings. Also, floor conditions and lighting in the laboratory were ideal during testing, where as actual mine environments seldom provide such conditions. In summary, operator distance from the continuous miner is a more important factor than rotational speed in reducing risk of injury during tramming. By maintaining a minimum of 910 mm (3 ft) distance to the machine, continuous miner operators can substantially reduce their risk of being struck. For roof bolter operators, a vertical boom operating speed of less than 330 mm/sec (13 in./sec) results in a decreased risk of contacting the machine, and a horizontal operating speed of 30 mm/sec (12 in./sec) or less results in a decreased risk of contact in all cases except in the 1,220 mm (48 in.) seam height with the kneeling posture. In that case, additional research needs to be conducted to determine safe boom speeds.

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