A Simulation Approach Analyzing Random Motion Events Between a Machine and its Operator

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ABSTRACT

This paper presents an approach for representing and analyzing random motions and hazardous events in a simulated three-dimensional workplace, providing designers and analysts with a new technique for evaluating operator-machine interaction hazards in virtual environments. Technical data in this paper is based upon a project striving to reduce workers' risks from being hit by underground mining machinery in a confined space. The project's methodology includes human factors design considerations, ergonomic modeling and simulation tools, laboratory validation, and collaboration with a mining equipment manufacturer. Hazardous conditions can be analyzed in virtual environments using collision detection. By simulating an operator's random behavior and machine's appendage velocity, researchers can accurately identify hazards, and use that information to form safe design parameters for mining equipment. Analysts must be discerning with the model and not read more from the databases than what the simulation model was designed to deliver. Simulations provided an interesting approach to data gathering in that there was no need for live subjects and logistics – test sites and costs associated with experiments–became insignificant. Collisions versus speed, operators' size, and risk behaviors proved the versatility found in the data obtained from the model. Preliminary results show that response time significantly affects the number of collisions experienced by the virtual subject. Also simulation data suggests that more mishaps occur with hand-on-boom-arm risk behavior.

INTRODUCTION

Several injuries to operators of underground coal mining equipment have led an investigation of safe velocities of a roof bolter boom arm at the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory (PRL). Researchers considered studying actual mishaps but empirical data cannot be collected from the incidents. They also considered laboratory experimentation but the complexity and danger made experimentation impractical. Therefore, a computer-based, three-dimensional solid model simulation approach was used as the primary means to gather data on mishaps. In the model, mishap means two or more object properties interacting. Consequently, hazardous conditions were analyzed in virtual environments using collision detection.

The uncertainty or randomness inherent in the drilling task can be compared to someone drinking a can of beverage. The occurrence of lifting the can to one's mouth and placing it back onto the table top is considered a random motion, and one could easily visualize the path of that motion. To model the random motion, the sequence of someone drinking from a can of beverage would reoccur until the can is empty, and each motion-path would differ slightly even though the motions look alike. So the model would incorporate the randomness of the motion and path variance within that motion. Thus, for a machine and operator, the operator's various risk behaviors, motions of each risk behavior, and motion paths associated with each motion behavior and moving machine appendages have some degree of randomness. These random motions give the model a realistic representation of the operator's motions and behaviors found during any machine task.

A model that includes any random aspects must involve sampling, or generating random variate. The phrase "generating a random variate" means to observe or realize a random variable from some desired arrangement of values of variables showing their observed or theoretical frequency of occurrence.

Studies on workers job performance, machinery and work environment has identified miners' risk and hazard exposures while bolting [1, 2]. More than two dozen bolting related problems (including specific human behaviors) were recognized as potential situations that could lead to injury or exposing workers to injury. Approaches to avoid these situations were suggested and applied at mining operations to evaluate specific problems in roof bolting tasks. A field study conducted a human factors analysis of hazards related to the movement of the drill head boom of a roof-bolting machine [3]. Seven recommendations to increase the safety of roof bolting operations were developed.

BACKGROUND

Roof bolting is one of the most basic and the most dangerous elements of underground mining operations. It is the principle method of roof support in mines, which is essential to ventilation and safety.

After miner crews remove a section of the coal seam, bolting equipment operators install bolts to secure sections of unsupported roof. A bolter crew's typical work sequence includes: general preparation and setup, drilling a hole, and installing a bolt. The sequence repeats until a section's roof is secure. The roof bolter operator does his or her job in a confined workspace near moving machinery. This restricted work environment puts the operator in awkward postures for tasks that require fast reactions to avoid being hit by the moving machine parts. Restricted visibility due to a protection canopy and low lighting conditions further complicates the task. From 1992 to 1996 Health and Safety Accident Classification injury data base showed an average of 961 roof bolter operator incidents per year, making roof bolting the most hazardous machine-related job in underground mining.

To address safety issues, the Mine Safety and Health Administration established a roof-bolter-machine committee with members from the WV Board of Coal Mine Health and Safety, NIOSH, and roof bolter manufacturers. The committee studied 613 accidents and 15 fatalities that attributed to inadvertent or incorrect actuation of control levers while the operator was within the drill head or boom pinch-point area (see figure 1). One major outcome of this study was the realization that there is no data on safe speeds for booms operating close to workers in confined environments like an underground coal mine. The NIOSH, PRL is endeavoring to determine what boom speed minimizes the roof bolter operator's chances of injury while still doing his or her job effectively.

METHODOLOGY

A computer-based simulation approach was used to generate and collect collision data between the machine and its operator while dealing with many variables, such as, the operator's response time, knee posture, choice of risk behavior, anthropology and machine's appendage velocity.

Engineering Animation's software, Transom JACK, was the simulation tool chosen to develop a roof bolter model for simulation. JACK is a human-centric visual simulation software package. Jack's software architecture lets users extend it's simulation functionality by writing code with the Lisp programming interface and Jack Command Language (JCL).

The roof bolter model evolved from code developed in Lisp and JCL that creates random human motion, random motion goals for the hands and torso, and random motion of events reflecting operator's behavior. The behavior motion parameters are based on statistics of machine and human actions that could cause injuries or fatalities in a bolter's workspace. The highest percent of hazardous acts were found in two bolter tasks: drilling the hole and installing a bolt [2]. The model contains only the task of drilling the hole, because it involves more risk behaviors: (1) hand on the drill bit (see figure 2a), (2) hand on the boom arm (see figure 2b), (3) hand on the boom arm and then hand on the drill bit, and (4) hand off the boom arm and drill bit (see figure 2c). Also, video footage of a roof bolter operation, in an actual underground coal mine and a manufacturer's training video, were used to help develop the animated motions of the operator in the model.

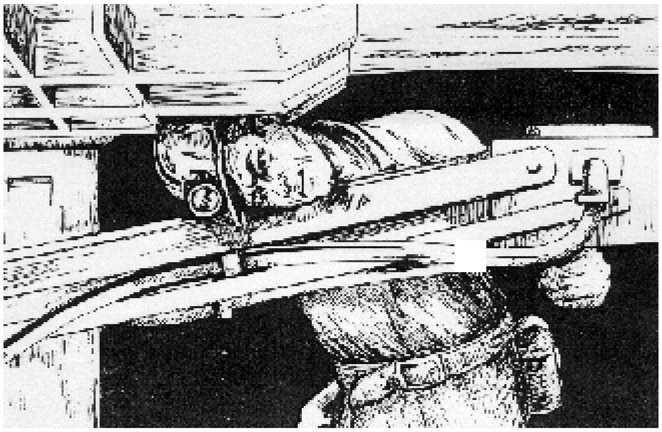

Figure 1. Artist concept of an operator caught within the boom arm pinch-point area.

The model allows investigators to experiment with response variable behavior (number of collisions between operator and machine) when manipulating the variables. Table 1 identifies all of the variables considered for the model. The operators' response times were withheld from the model because of proprietary issues and the complexity of programming this during simulation test runs. The response times were later used in the data analysis phase. During simulation runs, selected experimental conditions, shown in table 2, were held constant. The resulting simulation lets investigators generate, collect and analyze realistic data between a machine and its operator.

While watching animations produced by the software, the model seems to accurately depict random motions. The parameters used to generate random motions in the model need to be validated. If the model is valid then the decisions made with the model should be similar to those that would be made by physically experimenting with the roof bolter. Experiments on a full scale working mockup of a roof bolter boom arm are currently being conducted using human subjects to verify operator response times, human motion data, and field of view [4] relative to the bolter's boom arm. Because the model's validation stages are in progress, the results reflected in this paper include only preliminary simulation data.

RESULTS

The model can generate 96 different scenarios that mimic motions of the operator and machine during the drilling task. The scenarios are defined by varying four factors: four boom arm speeds [5], three operator heights, four risk behaviors and two knee postures. After the model generates motions, it records collisions that happen between the machine and its operator during a simulation test run. Distances between the operator's body parts and one or more of the six reference points on the boom arm are measured and recorded. The simulation's run time when the moving boom arm enters in the operator's viewing area is recorded. All information is collected every tenth of a second throughout a simulation test run. In the model's program, an output function sends each test run result to a computer file. In addition to recorded data, each file contains (1) a description of the test run scenario that characterizes which working behavior is in use, (2) whether the operator posture is leaning forward or is upright and (3) whether the operator is kneeling on one knee or on both knees. Table 3 shows the output file description. A typical test series consists of 600 simulation test runs.

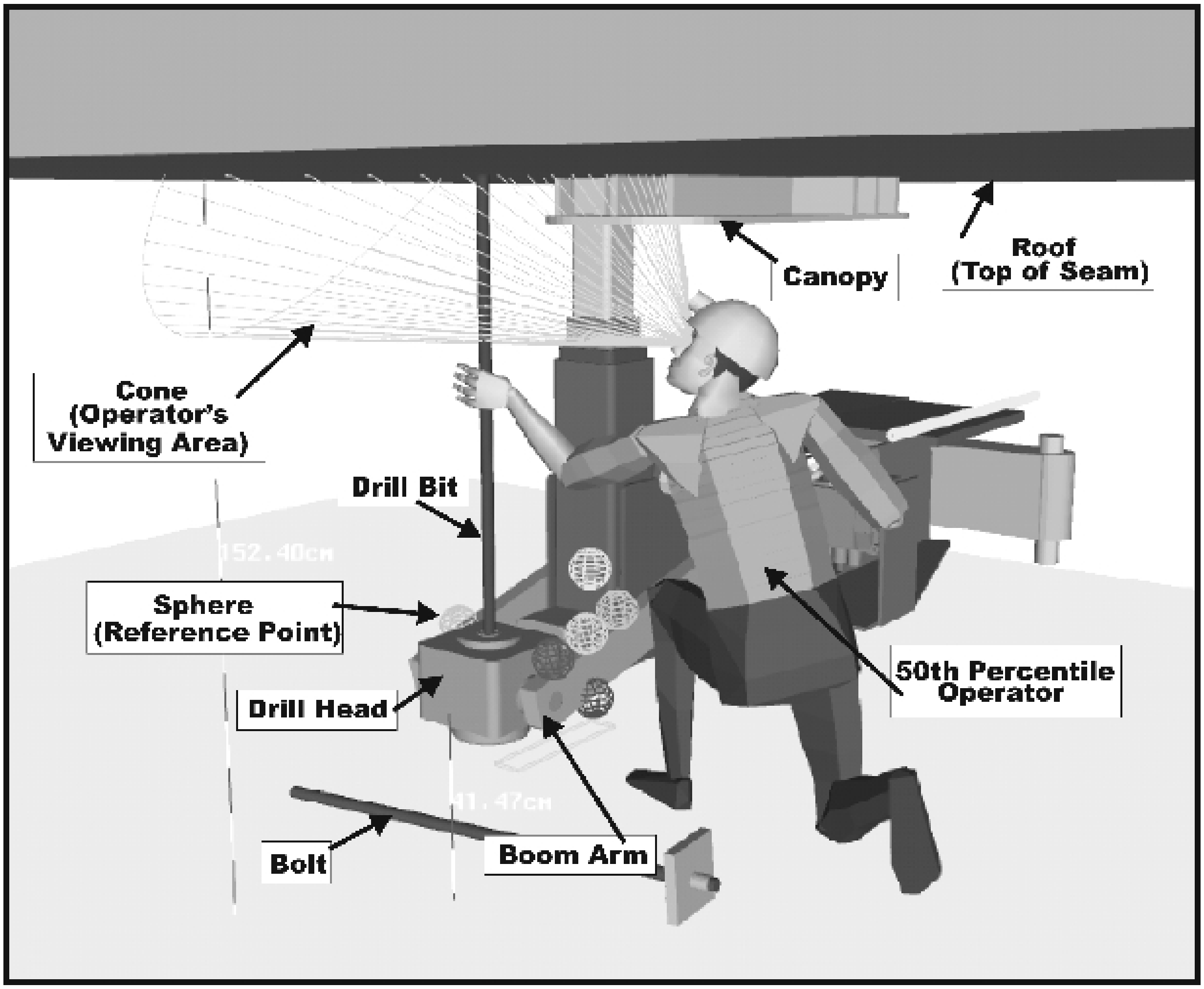

Figure 2a. Operator's risk behavior, hand on steel bit.

Figure 2b. Operator’s risk behavior, hand on boom arm.

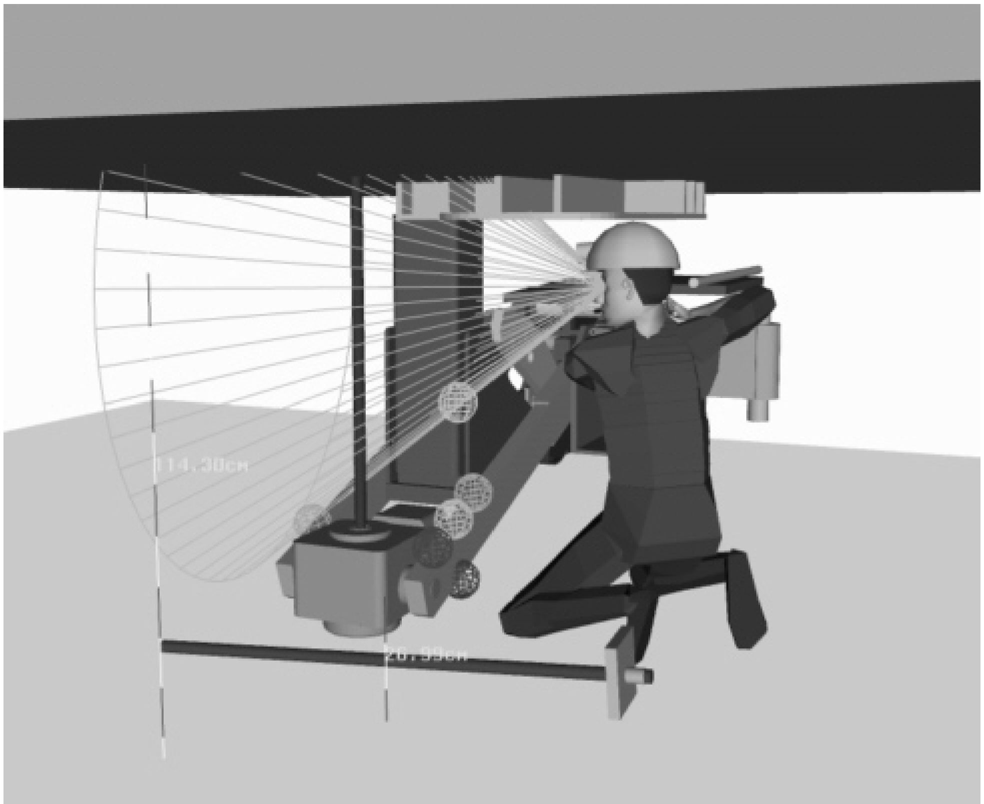

Figure 2c. Operator’s risk behavior, hand off steel bit and boom arm.

Table 1. Variables considered in the simulation model

Independent variables	
operator's anthropometric scale [9, 10, 11, 12, 13, 14] • 5th, 50th and 95th male percentile subjects	operator's random body motion • motion with some degree of randomness
initial work posture • operator's posture, one or two knees • randomly lean forward 0 to 30 degrees • position from the boom 0 to 20 cm closer	operator's optimal viewing area • ±40 deg vertical and ±35 deg horizontal to either side of the normal line of sight [4]
operator's response time • includes perceptual time, decision making time, and reaction time or motor response time (get out of the way)	risk behaviors associated with drilling • operator places hand on the steel bit {1,0}, places hand on the boom arm {0,1} or both hand on bit and then arm {1,1} or hand off both {0,0}
mine seam height typical for machines' model [1] • 114.3cm, 152.4 cm, and 182.8 cm	machine control panel configuration • piano key and joystick controls
protective canopy height • same height as the seam or removed	speed of boom arm and drill head • 17.78 cm/sec, 25.40 cm/sec, 40.64 cm/sec and 55.88 cm/sec
Dependent variables	
• *collisions* between the operator and selected machine appendages	
• *distances* between operator's body parts to reference points on the machine	
• *time-event-signal* when the operator sees the moving boom arm	
[1] Recommended by Fletcher & Co., Huntington WV, manufacturer of the Roof Ranger bolter.	

An important phase of data analysis is to create a database of each test series. This requires several steps. First, count the number of collisions ('raw') that occur in each test run. Second, determine the number of collisions ('avoid') in each test run that the operator could have avoided by using a predetermined human response time, taking 250 msec or 400 msec [6, 7, 8] to get out of the way of a moving boom arm once seen. Third, calculate the collision totals to be used for evaluation by taking the difference between 'raw' and 'avoid,' resulting in collisions (see table 4, 'hit') represented as four scatter plots (figures 3a, 3b).

A scatter plot gives strong support for using regression analysis. Regression analysis shows the relationships between independent variables and one dependent variable, such as taking into account the values of the five factors in the model and predicting collision trends. With one independent variable (speed), the regression analysis plots a line of "best fit" through a scatter plot of independent-dependent (speed-collisions) value pairs.

Along with regression analysis, a nesting technique is used on each collision database to group factors together, forming relationships that, when plotted, give meaningful trends. For example, a collision-versus-speed plot for a desired risk behavior would be depicted by three separate lines. Each line is identified by the operator's height, which includes both response times and knee postures. For each test series, unique collision-versus-speed plots were created using nesting techniques and varying the levels of the risk behavior. Simulation data regressions for a 114.3 cm (45 in) coal seam height and a 152.4 cm (60 in) coal seam height, are graphed in figures 4a, 4b through 8a, 8b.

Analysis of the databases reveals what happens when 'variables' change as they relate to the interactions between the operator and the machine:

- number of collisions versus boom arm speeds,

the significance of the

- operator's response time,
- knee posture,
- choice of risk behavior, and
- anthropology.

Table 2. Simulation Test Chart

Machine	**Machine Controls**	**Mine Info**	**Test Velocity**	**Test Subjects** **N = 50 each**
Type: Bolter	**Configurations:** Piano Key (pk) and Joystick (js)	**Seam Height (cm)** 114.3, 152.4 and 182.8	**Experiment Speed 1**	**Male Percentile 1**
				Male Percentile 2
				Male Percentile 3
			Experiment Speed 2	**Male Percentile 1**
				Male Percentile 2
				Male Percentile 3
			Experiment Speed 3	**Male Percentile 1**
				Male Percentile 2
				Male Percentile 3
			Experiment Speed 4	**Male Percentile 1**
				Male Percentile 2
				Male Percentile 3

Each factor level is held constant for each test speed and subject combination.

PLANNED TESTS:	pilot	experimental	research
Test series 1: pk, 152.4 cm	X	X	X
Test series 2: pk, 114.3 cm	X	X	X
Test series 3: pk, 182.8 cm	-	E2	E2
Test series 4: js, 152.4 cm	-	E1	X
Test series 5: js, 114.3 cm	-	E1	X
Test series 6: js, 182.8 cm	-	E2	E2

(4 speeds) X (3 subjects per speed) X (50 observations per subject) = 600 total observations per test series.

X: original testing; E1: 1st test expansion; E2: 2nd test expansion

Table 3. Output File Description

	Description
Top Line	identifies which risk behavior and posture are in use
Columns	(Note: "sphere.site# " is an object in the simulation environment and used as a reference point)
time	simulation time, which is converted from frames to seconds within the code
LB#5	reports the distance between the operator's "lower body site" and the sphere.site5
VCB	reports the number of collisions that occur between the cone viewing area and the boom arm; actually used for recording when the boom arm is seen by the operator
#4	distance between the cone view site and sphere.site4
#6	distance between the cone view site and sphere.site6
LPB	number of collisions between the left palm and the boom arm
LPD	number of collisions between the left palm and drill head
#2	distance between the left palm and sphere.site2
#4	distance between the left palm and sphere.site4
LAB	number of collisions between the left forearm and the boom arm
LAD	number of collisions between the left forearm and drill head
#2	distance between the left forearm and sphere.site2
#4	distance between the left forearm and sphere.site4
LLB	number of collisions between the left leg and the boom arm
LLD	number of collisions between the left leg and drill head
2#	distance between the left leg and sphere.site2
#4	distance between the left leg and sphere.site4
RLB	number of collisions between the right leg and the boom arm
RLD	number of collisions between the right leg and drill head
#2	distance between the right leg and sphere.site2
#4	distance between the right leg and sphere.site4
HDB	number of collisions between the head and the boom arm
#2	distance between the head and sphere.site2
#4	distance between the head and sphere.site4

Table 4. Simulation Scenarios from Experimental Observations (sample listing)

scenario	speed in/sec	operator height, in	response time, msec	risk behavior		postures	collision totals		
				{B1, B2}		knee	raw	avoid	hit
111111	7	63	250	0	0	2	7	5	2
111112	7	63	250	0	0	1	12	6	6
111121	7	63	250	0	1	2	10	5	5
111122	7	63	250	0	1	1	13	7	6
111211	7	63	250	1	0	2	2	1	1
111212	7	63	250	1	0	1	0	0	0
111221	7	63	250	1	1	2	0	0	0
111222	7	63	250	1	1	1	1	1	0
112111	7	63	400	0	0	2	7	5	2
112112	7	63	400	0	0	1	12	6	6
112121	7	63	400	0	1	2	10	5	5
112122	7	63	400	0	1	1	13	7	6
112211	7	63	400	1	0	2	2	1	1
112212	7	63	400	1	0	1	0	0	0
112221	7	63	400	1	1	2	0	0	0
112222	7	63	400	1	1	1	1	1	0
121111	7	69	250	0	0	2	0	0	0
121112	7	69	250	0	0	1	1	0	1
● ● ● ●									
432122	22	75	400	0	1	1	8	0	8
432211	22	75	400	1	0	2	0	0	0
432212	22	75	400	1	0	1	0	0	0
432221	22	75	400	1	1	2	0	0	0
432222	22	75	400	1	1	1	1	0	1

Collisions versus speed, operator's size, and risk behaviors demonstrate the versatility found in the data obtained from the model. Response time significantly affects the number of collisions experienced by the virtual subject (figures 4a, 4b). Also, simulation data indicates that lower seam heights have more mishaps and are more sensitive to the two response times in this experiment. Factors such as age, strength or other constraints relating to a person's reaction time could be used to generate a tailored response time. Experimental data (figures 5a, 5b thru 8a, 8b) indicates that more mishaps occur with risk behavior {0,1}, hands on the boom arm. The lower seam height significantly affect mishaps only in one risk behavior {0,1}, hands on the boom arm.

CONCLUSION

Ergonomists who provided technical support for this work were overwhelmed with the infinite possibilities of test scenarios, because there were no limitations placed on the virtual human operator. Simulations also provided an interesting approach to data gathering in that logistics–mine sites and costs associated with experiments–became insignificant. The model requires further enhancements to streamline its efficiency. For example, the model's code undergoes numerous but minor changes to accommodate all test series and setups of each simulation test run. Automating the modification procedure that changes the code would improve the model's ease of use. Also, at present there is no automatic scheme in the model to detect when the boom arm enters and leaves an operator's viewing area. Response times rely on this information. Thus the time element used to ascertain what collisions could have been avoided is performed manually by examining each data run file and 'observing' when this event occurs. Automating it would quicken data analysis and virtually eliminate any possible inaccuracies manual observations could cause.

The following general recommendations can be made upon the outcome of this work. The model is only as good as the system it defines; basically certain parameters must be validated using real subjects. Second, analysts must be discerning with the model and not read more from the databases than what the model was designed to deliver. Finally, increasing the model's ease of use will be essential if industry finds value in the simulation approach presented in this paper as a research tool.

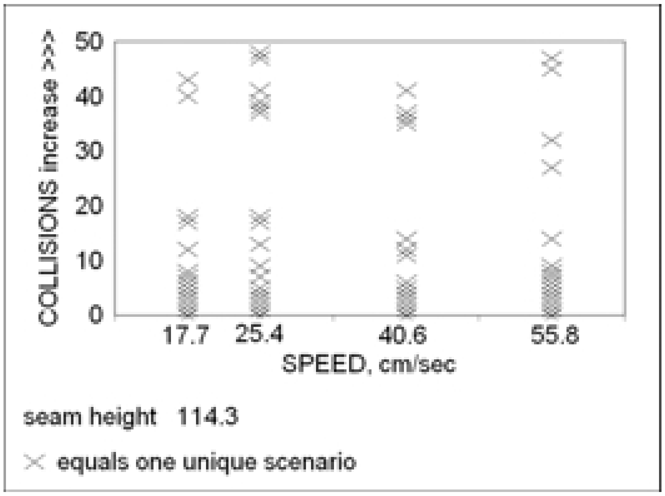

Figure 3a. Collision totals of scenarios vs. machine boom arm speed in a 114.3 cm seam.

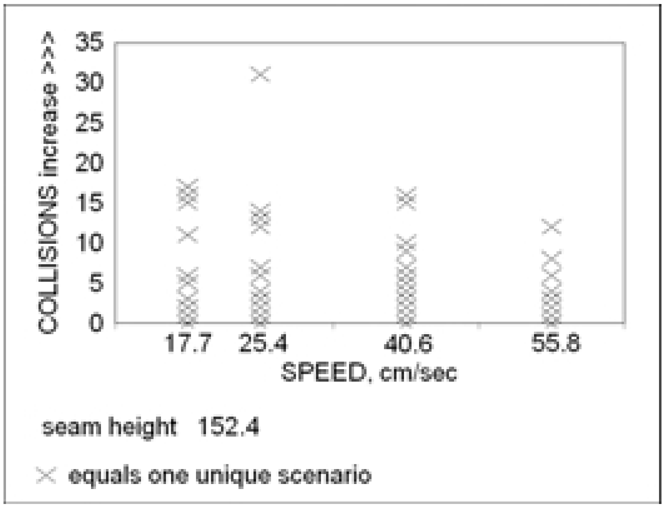

Figure 3b. Collision totals of scenarios vs. machine boom arm speed in a 152.4 cm seam.

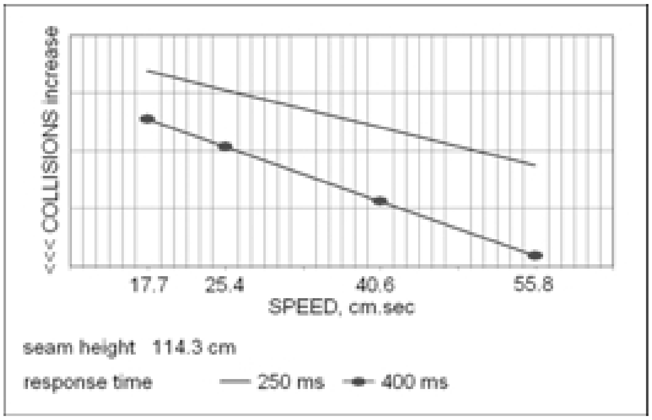

Figure 4a. Collisions vs. machine boom arm speed and operator response time in a 114.3 cm seam.

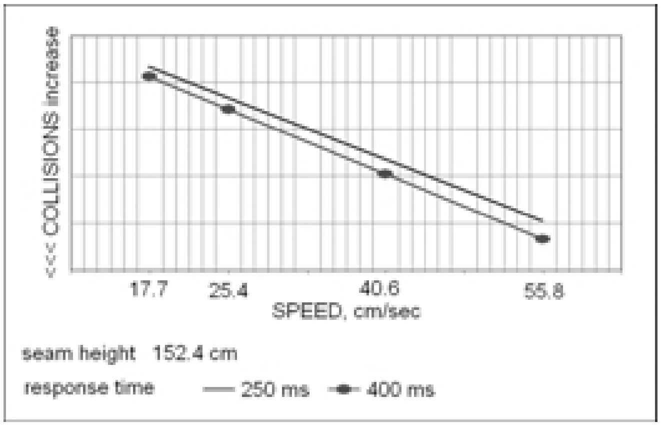

Figure 4b. Collisions vs. machine boom arm speed and operator response time in a 152.4 cm deam.

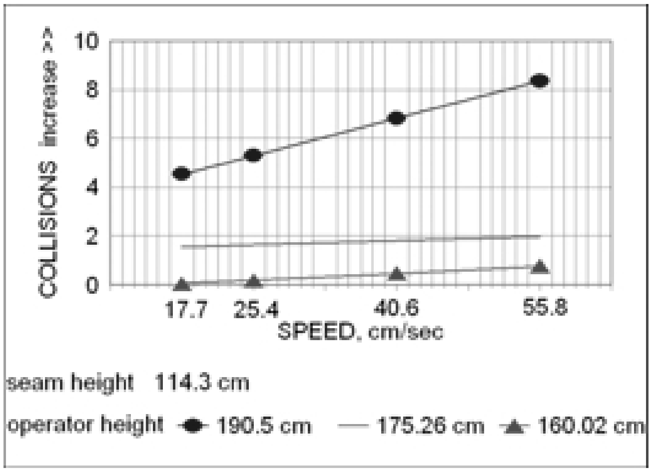

Figure 5a. Collisions vs. machine boom arm speed and operator at risk behavior {0,0} in a 114.3 cm seam.

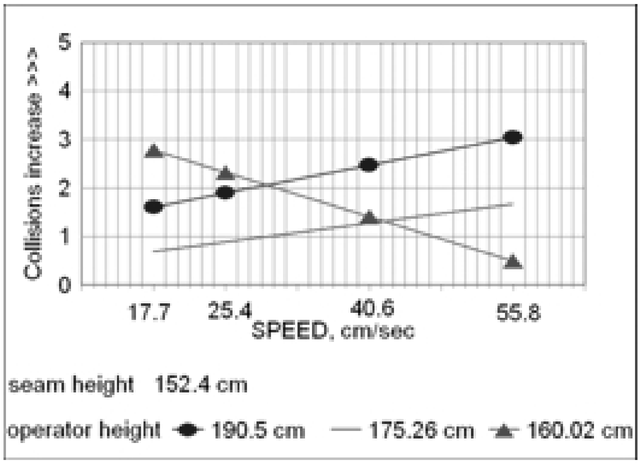

Figure 5b. Collisions vs. machine boom arm speed and operator at risk behavior {0,0} in a 152.4 cm seam.

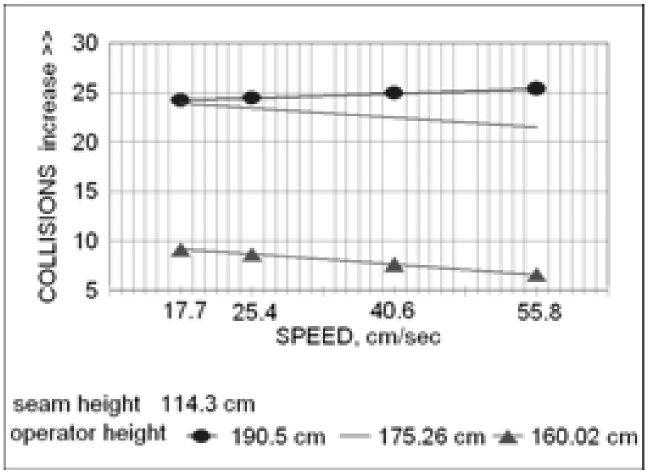

Figure 6a. Collisions vs. machine boom arm sped and opeator at risk behavior {0,1} in a 114.3 cm seam.

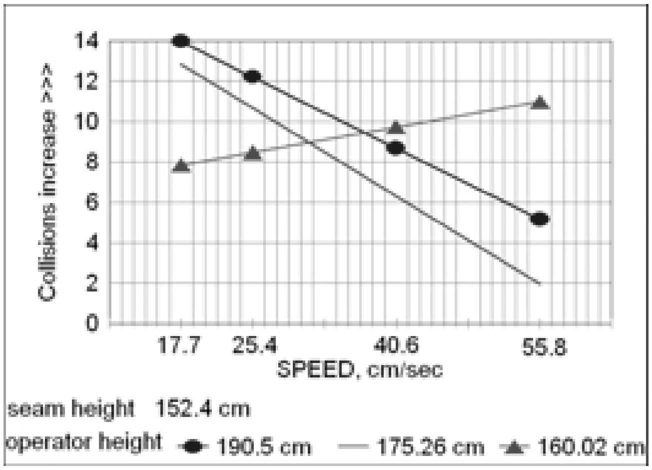

Figure 6b. Collisions vs. machine boom arm speed and operator at risk behavior {0,1} in a 152.4 cm seam.

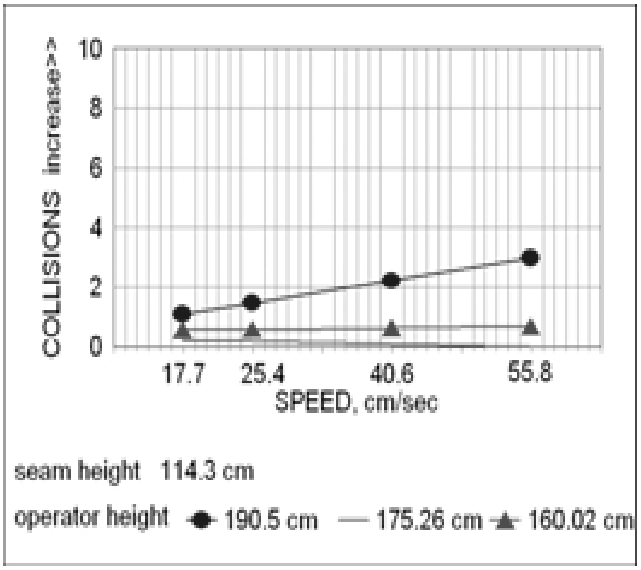

Figure 7a. Collisions vs. machine boom arm speed and operator at risk behavior {1,0} in a 114.3 cm seam.

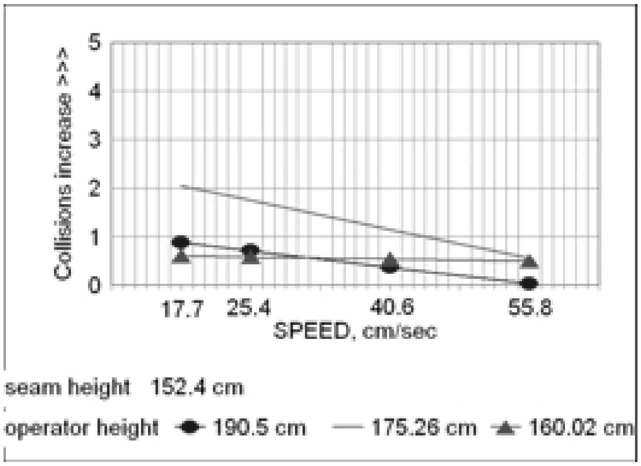

Figure 7b. Collisions vs. machine boom arm speed and operator at risk behavior {1,0} in a 152.4 cm seam.

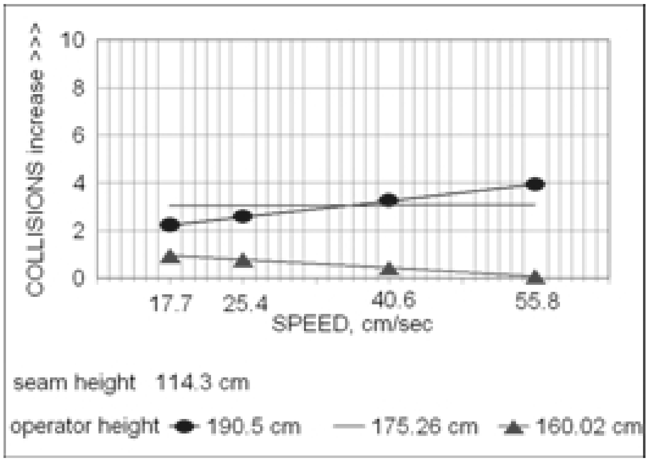

Figure 8a. Collisions vs. machine boom arm speed and operator at risk behavior {1,1} in a 114.3 cm seam.

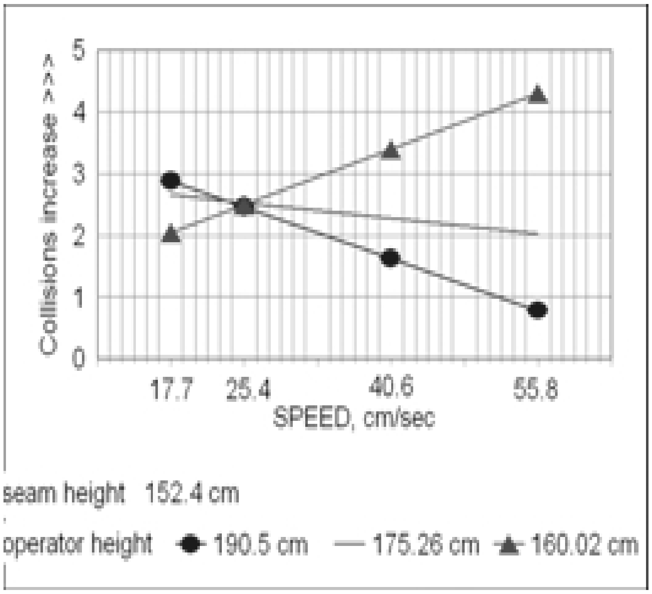

Figure 8b. Collisions vs. machine boom arm speed and operator at risk behavior {1,1} in a 152.4 cm seam.

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