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Optimizing seat selection for LHDs in the underground mining environment

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Synopsis

Whole-body vibration (WBV) occurs when the human body is supported on a surface that is vibrating. Operators and passengers in mobile machinery are exposed to vibration transferred from the seatpan to the body. Excessive vibration exposure is strongly associated with low back pain, therefore seat selection is important for reducing vibration exposure. Recently, we developed an efficient neural network (NN) algorithm that identified the dynamic properties of suspension seats, and then interrogated the models to predict seatpan vertical accelerations for a variety of skidders in the forestry sector. We have expanded this approach to evaluate the influence of different seats on the WBV exposures from load-haul-dump vehicles in the underground mining environment. Of the five seat models that we tested, our results demonstrated that one particular seat model was best able to attenuate vibrations based on the equivalent daily exposure, $A(8)$, and the corresponding working hours to reach the upper limit of the ISO 2631-1 health guidance caution zone for 8-hour operation. We performed a sensitivity analysis to evaluate the influence of the individual vibration frequency components on the $A(8)$ results for each of the seat models. This analysis revealed that each of the industrial seats responded differently to specific vibration frequencies and explained why the seat selection algorithm matched particular seats to specific vibration environments.

Keywords

neural network, seat selection, whole-body vibration, $A(8)$, health guidance caution zone, sensitivity analysis.

Introduction

Whole-body vibration (WBV) occurs when vibration at the seat is transmitted to mobile machinery operators (Morgan and Mansfield, 2011). WBV is associated with an increased risk of low back pain (LBP) when operators are exposed to vibrations while in a sitting posture (Johanning, 2011; Lis *et al.*, 2007). More than 25% of employees are affected by LBP each year (Lee *et al.*, 2001). LBP is considered to be a widespread health problem and is a severe complaint amongst occupational operators exposed to WBV (Bovenzi and Betta, 1994; Davis and Jorgensen, 2005; Seidel, 2005).

Load-haul-dump (LHD) vehicles are commonly used to excavate large quantities of ore or rocks in underground mining environments. ISO 2631-1 standard (1997) presents tools to evaluate the health risk by calculating the frequency-weighted accelerations of vibration exposures. Several studies reported that operators of LHD vehicles are exposed to high-magnitude WBV which often exceed the ISO 2631-1 health guidance caution zone (HGCZ) (Aye and Heyns, 2011; Eger *et al.*, 2006, 2011; Kumar, 2004; Mandal and Srivastava, 2010; Smets, Eger, and Grenier, 2010; van Niekerk, Heyns, and Heyns, 2000; Village, Morrison, and Leong, 1989). LHDs are commonly associated with compensation claims (Burgess-Limerick, 2005), and one study reports that LHD operators experience LBP 4.25 times more frequently than control subjects who are not exposed to occupational WBV (Mandal and Srivastava, 2010).

Vibration exposure is influenced by some individual vibration factors (*e.g.* magnitude) (ISO 2631-1, 1997) and modulating factors (*e.g.* terrain type, vehicle mass, *etc.*) (Donati, 2002). Seats also influence the vibration exposure transmitted to the heavy machine operators (Griffin *et al.*, 2006; Gunaselvam and van Niekerk, 2005). Due to the frequency-dependent properties of the suspension system, industrial seats should be selected appropriately for the specific vehicles or workplaces (Gunaselvam and van Niekerk, 2005). Inappropriate choice of seat or incorrect adjustment of a seat suspension system can amplify vibration exposure (Paddan and Griffin, 2002).

Neural network (NN) models have been utilized in a wide range of applications because of their versatility for describing relationships between variables (May, Zhou, and Lee, 2012; Widrow *et al.*, 2013; Won *et al.*, 2010). NNs can model complex nonlinear relationships between the measured system's

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input and output signals by adjusting the weights and biases between neurons to optimize the predictions. An efficient NN model approach (Ji, Eger, and Dickey, 2015) has been successfully developed and used to identify the vibration attenuation properties of five commercial industrial seats that are commonly used in heavy mobile machinery. That study determined that one industrial seat was the most suitable for the specific vibration exposure for skidders in forestry workplaces (Ji, Eger, and Dickey, 2015). The primary purpose of the current paper is to apply this NN approach to LHD equipment, and evaluate whether specific industrial seats perform well for LHDs in underground mining environments. A second purpose is to identify the performance of these industrial seats at specific vibration frequencies by evaluating the effects of the individual frequency components on the equivalent daily exposure ($A(8)$) results, and reveal why the seat selection algorithm matched particular seats to specific vibration environments.

Methodology

The development of the NN models for the five industrial seats was described in a previous study (Ji *et al.*, 2015). The essential elements of this process are presented here for completeness.

Each of the industrial seats tested (Access Mining Services model 30019932, model Amobi SM2024; Sears Manufacturing Co. model CAT EW013121; KAB Seating Ltd KAB 301, KAB 525) was mounted to the top surface of a six degree of freedom (6df) robotic platform (R3000, Mikrolar Inc. Hampton, NH, USA), which produced 6df vibrations based on a library of occupational field vibration exposures (Dickey, Eger, and Oliver, 2010) and 3df broadband (0.5-20 Hz, r.m.s. amplitudes between 0.2 and 2.0 m s^2 on all three translational axes) random frequency profiles (Ji, Eger, and Dickey, 2015). Each seat's suspension was appropriately adjusted to its mid-travel position (to avoid hitting the end-stops). Two 6df inertial measurement units (IMUs; MechTrack – analog version, Mechworks Systems Inc., West Vancouver, BC, Canada) were used to record accelerations at the seatpan/operator interface and the centre surface of the robotic platform (chassis) as recommended in ISO 2631-1 (1997). This chassis and seatpan acceleration data was collected from ten subjects with a range of anthropometrics.

The five-layer neural identification NNs' inputs were the recorded time-series translational chassis acceleration data and the *BMI Prime* for each subject. *BMI Prime*, equal to *BMI* divided by 25 (Gadzik, 2006), reflected the machine operators' anthropometrics. Each neuron in the second layer acted as a bandpass filter for the time series chassis data on three translational axes. The root mean square (r.m.s.) values of the recorded chassis acceleration data was calculated in the third layer and were combined with the corresponding *BMI Prime* value from the first layer to predict the vertical r.m.s. accelerations of the seatpan in the fourth layer. Each seat model was represented by the optimal weights and biases that linked the different NN layers. These optimal weighting parameters were determined through a system identification process by matching the predicted outputs (r.m.s. acceleration) to the corresponding measured values in the processing fifth layer. Although the NN structure was identical for each of the seat models, the weighting parameters differed and uniquely described the performance of each of the seats. The NN models robustly described the relationship between measured and predicted seatpan r.m.s. accelerations; the coefficients of determination (r^2) ranged between 0.97–0.99 for the training profiles, and between 0.93–0.96 for the validation profiles.

For the current study, we implemented each of our robust seat models to predict the daily 8-hour equivalent frequency-weighted accelerations (ISO 2631-1, 1997), $A(8)$, for ten LHD vehicles from our library (Dickey, Eger, and Oliver, 2010) of previously reported field data (Eger, Kociolek, and Dickey, 2013) (Table I). The ISO 2631-1 W_d and W_k filters were used to process the horizontal (x- and y-axis) and the vertical (z-axis) chassis acceleration data collected from the mining workplace measurements respectively. Each axis was multiplied by the appropriate k factors for health assessment (*e.g.* k_x=k_y=1.4 and kz=1.0) to obtain the frequency-weighted chassis accelerations (ISO 2631-1, 1997). The r.m.s. values of the weighted chassis vibration data were calculated using bandpass filters (0.5–20 Hz) in the x- and y- axes, and one-third octave filters (0.5–20 Hz) in the z-axis. Three specific *BMI Prime* values (0.74, 1.00, and 1.20) were selected to reflect the influence of machine operator anthropometrics. Then we used these weighted r.m.s. values as inputs of each NN model to predict the weighted r.m.s. accelerations of the seatpan in the vertical direction. Similarly to previous studies (Aye and Heyns, 2011; Eger, Contratto, and Dickey, 2011), $A(8)$ values were calculated from the predicted frequency-weighted seatpan r.m.s. acceleration and the corresponding duration proportion of each machine operation task (Table I). We also estimated the number of working hours to reach the upper acceleration limit (0.9 m/s^2) of the ISO 2631-1 HGCZ for 8 hours of vibration exposure to effectively evaluate the health risk for operators and to select the most suitable seat for this mining environment.

In order to describe the frequency spectra of the vibration data, we calculated the one-third octaves between 0.5 and 20 Hz using the sound and vibration toolkit for LabVIEW (V10.0.1, National Instruments, Austin, TX) for each of the specific mining vehicles. Given the different vibration environment for skidders in the forestry workplace, we also performed this one-third octave analysis on the vibration data from eight skidders for comparison (Ji *et al.*, 2015). We also performed a sensitivity analysis to gain insight into which of the input parameters most strongly influenced the output of each seat NN model. The sensitivity analysis consisted of evaluating the impact of perturbing the amplitudes of specific frequencies of the individual vehicle acceleration profiles; the acceleration magnitude in each of the one-third octave bands was perturbed up and down 50% towards the maximum and minimum range, and the $A(8)$ acceleration magnitude was recalculated. Frequency bands that strongly influenced the output of the NN model will have a large range of $A(8)$ magnitudes when their amplitude is perturbed. The *BMI Prime* was set to 1.0 for these sensitivity analyses.

Results

The predicted seatpan accelerations for this group of 10 LHDs were large; of the 150 scenarios (10 LHDs, 3 operator BMIs, and 5 seats) only two (two operator BMIs for one LHD) were

Table I

Frequency-weighted vibration data (min., max., median) for the 20 s vibration segments for each of the ten LHD vehicles. The size of the vehicle (bucket capacity) and the distribution of machine operations (mucking, dumping, driving loaded, and driving unloaded) are also presented

Vehicle, bucket capacity	Operation	# of 20s segments		Ax (m/s/s)	Ay (m/s/s)	Az (m/s/s)	Roll (rad/s/s)	Pitch (rad/s/s)	Yaw (rad/s/s)
M1 10 cubic yard	Mucking	10	min.	1.07	1.38	0.90	3.35	3.72	2.98
			max.	2.07	2.08	1.60	3.79	4.71	3.52
			median	1.66	1.82	1.28	3.54	3.99	3.21
	Dumping	1	min.	--	--	--	--	--	--
			max.	--	--	--	--	--	--
			median	1.94	2.20	2.39	4.42	5.97	4.18
	Driving loaded	64	min.	0.99	0.64	0.92	3.37	3.61	2.91
			max.	2.25	2.01	2.57	7.09	6.53	4.59
			median	1.64	1.08	1.25	3.87	4.51	3.36
	Driving unloaded	76	min.	0.96	0.63	0.88	3.35	3.76	2.93
			max.	2.49	2.59	2.93	7.55	7.48	4.75
			median	1.54	1.11	1.14	3.86	4.52	3.39
M2 10 cubic yard	Mucking	0	min.	--	--	--	--	--	--
			max.	--	--	--	--	--	--
			median	--	--	--	--	--	--
	Dumping	9	min.	1.46	1.73	1.02	3.22	3.98	3.07
			max.	2.11	2.03	1.92	4.26	6.37	4.53
			median	1.82	1.83	1.47	3.64	4.72	3.42
	Driving loaded	28	min.	1.57	1.04	1.16	3.45	4.12	3.10
			max.	2.92	1.98	2.38	4.15	4.88	3.52
			median	2.07	1.22	1.35	3.67	4.34	3.29
	Driving unloaded	23	min.	1.93	0.98	1.43	3.37	4.15	3.06
			max.	2.64	1.82	2.43	4.11	5.33	3.57
			median	2.44	1.19	1.55	3.52	4.55	3.24
M3 10 cubic yard	Mucking	13	min.	0.78	0.93	1.30	2.88	3.18	3.00
			max.	1.84	1.84	2.56	3.28	3.79	3.24
			median	1.14	1.20	1.66	3.00	3.29	3.10
	Dumping	10	min.	0.67	0.93	0.93	2.80	3.15	2.82
			max.	1.25	1.57	2.14	3.04	3.36	3.20
			median	0.87	1.20	1.43	2.93	3.27	2.96
	Driving loaded	23	min.	0.55	0.61	0.29	2.77	3.07	2.68
			max.	1.13	2.48	2.09	3.12	3.43	3.00
			median	0.83	1.53	0.59	2.87	3.15	2.83
	Driving unloaded	41	min.	0.72	0.32	0.24	2.75	3.08	2.78
			max.	1.84	2.26	1.64	3.03	3.62	3.14
			median	1.11	1.23	0.76	2.89	3.17	2.88
M4 8 cubic yard	Mucking	21	min.	0.61	0.70	0.42	2.80	2.64	3.27
			max.	2.60	2.78	2.02	6.60	3.51	9.90
			median	1.53	1.71	1.51	3.42	2.90	4.13
	Dumping	4	min.	0.76	1.16	1.32	2.92	2.77	3.38
			max.	1.22	1.22	1.53	3.27	2.87	3.57
			median	0.94	1.20	1.42	3.00	2.81	3.51
	Driving loaded	68	min.	0.22	0.25	0.46	2.73	2.62	3.07
			max.	1.49	1.99	1.45	3.31	2.97	3.85
			median	0.92	0.98	1.01	2.87	2.78	3.22
	Driving unloaded	80	min.	0.51	0.34	0.34	2.71	2.64	3.02
			max.	1.75	1.85	2.60	3.94	3.07	5.33
			median	0.90	0.87	1.09	2.85	2.76	3.22
M5 8 cubic yard	Mucking	33	min.	0.79	1.07	1.61	2.79	3.46	2.88
			max.	1.78	1.84	4.08	3.30	5.69	3.62
			median	1.21	1.52	2.88	2.96	4.21	3.05
	Dumping	17	min.	0.23	0.63	0.40	2.63	3.30	2.65
			max.	0.93	1.39	1.59	2.87	3.75	3.11
			median	0.56	0.91	0.90	2.71	3.47	2.80
	Driving loaded	38	min.	0.48	0.65	0.68	2.70	3.29	2.71
			max.	1.52	1.37	4.05	2.96	4.27	2.98
			median	1.00	1.04	2.10	2.83	3.57	2.83
	Driving unloaded	41	min.	0.34	0.73	0.47	2.63	3.19	2.63
			max.	1.43	1.94	3.65	3.01	5.26	3.10
			median	1.01	1.10	1.93	2.80	3.53	2.81

Table I (Continued)

Frequency-weighted vibration data (min., max., median) for the 20 s vibration segments for each of the ten LHD vehicles. The size of the vehicle (bucket capacity) and the distribution of machine operations (mucking, dumping, driving loaded, and driving unloaded) are also presented

Vehicle, bucket capacity	Operation	# of 20s segments		Ax (m/s/s)	Ay (m/s/s)	Az (m/s/s)	Roll (rad/s/s)	Pitch (rad/s/s)	Yaw (rad/s/s)
M6 3.5 cubic yard	Mucking	6	min.	1.10	0.71	0.84	3.00	2.73	2.75
			max.	1.75	1.72	2.20	4.16	3.28	3.27
			median	1.30	1.41	1.65	3.44	2.94	2.83
	Dumping	4	min.	0.76	1.16	1.32	2.92	2.77	3.38
			max.	1.22	1.22	1.53	3.27	2.87	3.57
			median	0.94	1.20	1.42	3.00	2.81	3.51
	Driving loaded	24	min.	0.85	0.72	0.88	3.08	2.77	2.78
			max.	1.64	1.51	2.56	3.82	4.55	3.32
			median	1.33	1.09	1.69	3.33	2.95	2.93
	Driving unloaded	16	min.	1.06	1.23	1.62	3.31	2.99	2.83
			max.	2.49	2.01	3.36	4.95	7.06	3.58
			median	2.00	1.65	2.84	4.05	3.57	3.14
M7 3.5 cubic yard	Mucking	2	min.	2.10	1.33	2.21	4.93	3.84	3.63
			max.	2.32	1.50	3.07	6.16	7.19	3.80
			median	--	--	--	--	--	--
	Dumping	0	min.	--	--	--	--	--	--
			max.	--	--	--	--	--	--
			median	--	--	--	--	--	--
	Driving loaded	42	min.	2.33	1.18	1.14	4.05	2.67	2.74
			max.	4.00	2.17	2.98	8.23	3.69	4.01
			median	3.34	1.85	1.52	4.72	2.82	2.93
	Driving unloaded	97	min.	1.39	0.61	0.98	3.39	2.71	2.71
			max.	4.37	2.50	5.37	10.35	6.97	5.93
			median	3.33	1.73	1.90	4.87	2.98	3.08
M8 6 cubic yard	Mucking	7	min.	0.78	0.68	0.87	2.86	3.19	2.72
			max.	1.61	1.33	1.73	3.54	3.55	2.75
			median	1.32	1.07	1.31	3.12	3.36	2.74
	Dumping	5	min.	0.58	0.83	1.31	2.92	3.23	2.65
			max.	0.90	1.16	1.91	3.29	3.58	2.78
			median	0.73	0.98	1.76	3.09	3.32	2.75
	Driving loaded	81	min.	0.72	0.76	0.67	2.88	3.17	2.62
			max.	1.73	2.36	2.39	3.65	3.96	2.86
			median	1.17	1.05	1.34	3.17	3.34	2.73
	Driving unloaded	73	min.	0.91	0.74	0.84	2.94	3.18	2.61
			max.	1.71	1.77	3.04	3.54	3.72	2.89
			median	1.23	1.08	1.72	3.17	3.41	2.73
M9 2 cubic yard	Mucking	37	min.	0.98	0.87	1.16	2.71	3.12	3.12
			max.	2.20	3.21	3.85	5.19	8.29	5.23
			median	1.54	2.30	2.17	3.16	4.89	3.82
	Dumping	0	min.	--	--	--	--	--	--
			max.	--	--	--	--	--	--
			median	--	--	--	--	--	--
	Driving loaded	22	min.	0.95	1.38	1.32	2.74	3.00	3.00
			max.	1.74	1.88	2.44	3.22	4.11	3.47
			median	1.46	1.73	1.69	2.87	3.35	3.18
	Driving unloaded	24	min.	1.03	1.53	1.51	2.79	3.14	3.08
			max.	2.11	2.78	4.20	3.77	5.86	4.26
			median	1.84	2.36	3.53	3.38	4.91	3.77
M10 2 cubic yard	Mucking	0	min.	--	--	--	--	--	--
			max.	--	--	--	--	--	--
			median	--	--	--	--	--	--
	Dumping	0	min.	--	--	--	--	--	--
			max.	--	--	--	--	--	--
			median	--	--	--	--	--	--
	Driving loaded	7	min.	1.25	0.86	1.38	3.21	2.90	2.68
			max.	1.53	1.43	1.97	4.23	3.25	3.50
			median	1.42	1.04	1.51	3.31	3.00	2.83
	Driving unloaded	12	min.	1.25	0.83	1.44	3.24	2.95	2.75
			max.	1.69	1.73	2.23	6.46	4.72	6.61
			median	1.59	1.37	1.90	4.72	3.65	3.63

below the lower border of the ISO 2631-1 HGCZ, 30 were within the HGCZ, and 118 were above the HGCZ (Table II). On average, subjects with smaller *BMI Prime* values were predicted to experience larger average daily vibration exposures $A(8)$ than subjects with larger *BMI Primes* (Table II).

One LHD (M4) had lower predicted acceleration levels for all *BMI Prime* values and all seats ($A(8)$ = 0.39–0.69 m/s²) compared to the other LHDs; all driver and seat combinations could be tolerated for more than 8 hours (Table III). In contrast, several LHDs (M5, M6, M7, M9, M10) had higher acceleration levels ($A(8)$ = 1.05–1.89 m/s²) such that none of the driver and seat combinations could be tolerated for 8 hours (range from 1.82 to 5.88 hours). Specific seats in some LHDs (M1, M2, M3, M8) reduced the vibration exposure such that exposures could be tolerated for more than 8 hours while other seats in these vehicles could not be tolerated for 8 hours. The KAB301 seat reduced the vibration magnitude to levels that could be tolerated for more than 8 hours more often than the other seats; 14 of the 30 vehicle and driver combinations could be tolerated for more than 8 hours for the KAB301 seat compared to three each for the Access and Amobi seats, and six each for the CAT and KAB525 seats.

For the specific LHD vehicles M1, M2, and M8, the KAB301 seat was the only seat model to attenuate the occupational vibration exposures to below the upper acceleration limit of the ISO 2631-1 HGCZ (0.9 m/s²); the KAB301 seat attenuated the vibrations approximately twice as well as the CAT seat for these specific vehicles. In contrast, for four other LHD vehicles (M5, M6, M7, M9, and M10), the KAB301 seat and CAT seat performed similarly with all $A(8)$ values larger than 0.9 m/s².

Given these differences in performance of the KAB301 seat between vehicles, we examined the frequency spectra of the vibration exposures to evaluate whether there were differences in vibration exposures between vehicles; the chassis acceleration data for the ten LHDs was evaluated in one-third octave proportional frequency bands between 0.5 and 20 Hz. There did not appear to be striking differences in the vibration spectra between the vehicles where the KAB301 seat performed well (M1, M2, and M8) (Figure 1a) and those where the seat did not effectively attenuate the vibrations (M5, M6, M7, M9, and M10) (Figure 1b). For comparison, we also evaluated the chassis acceleration data for eight forestry skidders from our library of industrial vibration exposures (Cation *et al.*, 2008; Jack *et al.*, 2010). Figure 2 represents the data for LHDs M1, M2, and M8 where the KAB301 seat effectively attenuated the vibrations more effectively than the CAT seat, and the data for skidders S4, S5, S6, and S8 where the CAT seat attenuated the vibrations more effectively than

Table II

***A*(8) results for five industrial seats with different driver anthropometrics (*BMI primes*) in the underground mining environment**

LHDs	*BMI Prime*	*A*(8)* (m/s²)				
		Access	Amobi	CAT	KAB301	KAB525
M1	0.74	1.10	1.20	1.18	0.80	0.96
	1.00	1.06	1.11	1.10	0.74	0.92
	1.20	1.03	1.04	1.05	0.70	0.89
M2	0.74	1.04	1.15	1.21	0.80	0.92
	1.00	1.00	1.06	1.14	0.74	0.88
	1.20	0.97	0.99	1.09	0.69	0.85
M3	0.74	1.11	1.22	0.89	0.92	1.16
	1.00	1.08	1.14	0.82	0.86	1.13
	1.20	1.05	1.07	0.77	0.82	1.10
M4	0.74	0.60	0.69	0.50	0.66	0.69
	1.00	0.56	0.60	0.44	0.60	0.65
	1.20	0.53	0.53	0.39	0.56	0.62
M5	0.74	1.89	1.88	1.46	1.39	1.84
	1.00	1.85	1.79	1.39	1.33	1.81
	1.20	1.82	1.73	1.34	1.29	1.78
M6	0.74	1.54	1.58	1.39	1.15	1.43
	1.00	1.50	1.49	1.32	1.09	1.40
	1.20	1.47	1.42	1.27	1.05	1.37
M7	0.74	1.69	1.73	1.60	1.28	1.52
	1.00	1.65	1.64	1.53	1.22	1.49
	1.20	1.63	1.58	1.48	1.18	1.46
M8	0.74	1.24	1.30	1.15	0.87	1.12
	1.00	1.20	1.21	1.08	0.81	1.08
	1.20	1.16	1.14	1.03	0.77	1.05
M9	0.74	1.80	1.81	1.46	1.49	1.75
	1.00	1.76	1.73	1.39	1.43	1.71
	1.20	1.73	1.66	1.34	1.39	1.68
M10	0.74	1.56	1.63	1.58	1.45	1.47
	1.00	1.52	1.54	1.51	1.39	1.44
	1.20	1.49	1.47	1.45	1.35	1.41

*According to ISO 2631-1 the frequency weighted acceleration values corresponding to the lower and upper limits of the Health Guidance Caution Zone (for 8 h of exposure) are 0.45 and 0.90 m/s² respectively

Table III

The working hours to reach the upper limit of the ISO 2631-1 health guidance caution zone (HGCZ) for 8-hour working duration

LHDs	*BMI Prime*	Hours				
		Access	Amobi	CAT	KAB301	KAB525
M1	0.74	5.31	4.52	4.69	10.04*	6.98
	1.00	5.72	5.28	5.31	11.68*	7.58
	1.20	6.07	6.01	5.89	13.23*	8.09*
M2	0.74	5.99	4.91	4.41	10.18*	7.68
	1.00	6.48	5.79	4.98	11.88*	8.38*
	1.20	6.89	6.62	5.49	13.50*	8.98*
M3	0.74	5.21	4.34	8.17*	7.67	4.78
	1.00	5.59	5.03	9.65*	8.71*	5.09
	1.20	5.92	5.67	11.07*	9.65*	5.36
M4	0.74	17.96*	13.80*	25.45*	14.90*	13.72*
	1.00	20.45*	18.08*	33.71*	17.88*	15.33*
	1.20	22.70*	22.78*	42.79*	20.80*	16.75*
M5	0.74	1.82	1.84	3.05	3.37	1.91
	1.00	1.89	2.02	3.36	3.67	1.99
	1.20	1.96	2.17	3.62	3.92	2.05
M6	0.74	2.72	2.61	3.34	4.89	3.15
	1.00	2.86	2.92	3.70	5.42	3.32
	1.20	2.98	3.21	4.01	5.88	3.47
M7	0.74	2.27	2.18	2.53	3.96	2.80
	1.00	2.37	2.40	2.75	4.33	2.94
	1.20	2.45	2.60	2.94	4.64	3.05
M8	0.74	4.25	3.83	4.87	8.58*	5.20
	1.00	4.54	4.42	5.53	9.86*	5.58
	1.20	4.78	4.96	6.13	11.05*	5.90
M9	0.74	2.00	1.97	3.03	2.92	2.13
	1.00	2.09	2.18	3.33	3.16	2.22
	1.20	2.16	2.36	3.60	3.37	2.30
M10	0.74	2.66	2.43	2.60	3.07	2.98
	1.00	2.81	2.72	2.86	3.33	3.14
	1.20	2.92	2.98	3.08	3.56	3.28

*Indicates exposures that require more than 8 working hours to exceed the upper limit of the HGCZ for five industrial seats with different driver anthropometrics (*BMI Primes*) in the underground mining environment

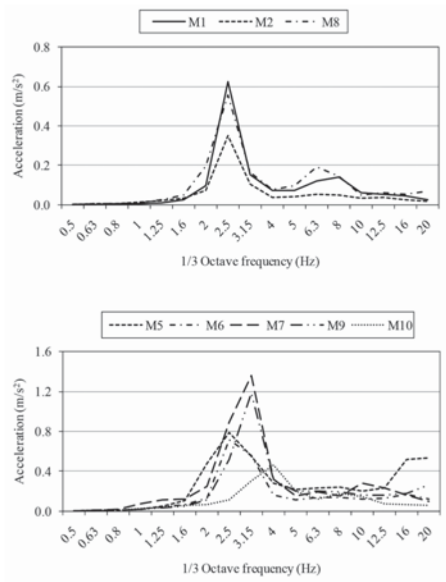

Figure 1—Chassis r.m.s. acceleration data for (a) three LHDs (M1, M2, and M8) and (b) five LHDs (M5, M6, M7, M9, and M10) at each one-third octave frequency band between 0.5 and 20 Hz. The KAB301 seat effectively attenuated the vibrations for the mining vehicles in Figure 1a, but not for those in Figure 1b

the KAB301 seat. These forestry vehicles had a dominant frequency of 2 Hz, while the mining vehicles had a dominant frequency of 2.5 Hz.

The $A(8)$ results for the LHDs are presented in Table II and the corresponding data for the skidder vehicles in the Appendix. The predicted $A(8)$ values from the sensitivity analyses (using the perturbed vibration amplitudes for each of the one-third octaves) for the CAT and KAB301 seats are presented in Figure 3. We focused on the three LHDs where the KAB301 seat effectively attenuated the vibrations (M1, M2, and M8); all three of these LHDs showed similar responses. The magnitude of the accelerations at 2.0, 2.5, 3.1, and 16.0 Hz resulted in large changes in the $A(8)$ values for both industrial seats. The KAB301 seat is highly sensitive to increases in magnitude of the 2 Hz and 3.15 Hz components (26% and 22% increase in $A(8)$, respectively) while the CAT seat is much less sensitive to increases in magnitude of these components (8% and 10% increase in $A(8)$, respectively). However, in the 2.5 Hz frequency band, the CAT seat is more sensitive to increases than the KAB 301 seat.

Discussion

Operators of heavy mobile machinery in the underground mining environment are subjected to large vibrations (Eger, Kociolek, and Dickey, 2013; Kumar, 2004; van Niekerk, Heyns, and Heyms, 2000). Seat selection is an important factor for reducing drivers' exposure to vibration (Gunaselvam and van Niekerk, 2005), but it is difficult to identify optimal seats due to the complexity of the seats' performance. We developed NN models characterizing the vertical attenuation properties of five common industrial seats (Ji, Eger, and Dickey, 2015) and predicted their performance for LHD vehicles from our library of occupational vibration exposures (Dickey, Eger, and Oliver, 2010). We evaluated the performance of five industrial seats based on the chassis vibrations measured for each of ten specific LHD vehicles and three variations of driver anthropometrics. Overall, the vibration environment for these ten vehicles was such that relatively few of the seats were effective at reducing the vibration exposure such that the workers could be exposed for 8 or more hours (32 of 150 seat-operator-vehicle combinations). Among the five seats tested in this study, our predictions indicate that the KAB301 seat was the best choice in the mining environment; it had the lowest $A(8)$ and largest number of hours to reach the upper boarder to the HGCZ for seven of the vehicles, and was ranked second for two other vehicles, although the vibration magnitudes were similar to the best-ranked seat. All of the seats were predicted to perform well for one of the vehicles. In terms of absolute vibration magnitude, the KAB301 seat allowed approximately half of the specific operator/vehicle combinations (14 of 30) to be operated for over 8 hours in the mining environment. The KAB301 seat attenuated the magnitudes of the vibration exposures for these operator-vehicle combinations below the upper limit (0.9 m/s^2) of ISO 2631-1 HGCZ, which minimized the health risks of exposure for heavy machine operators. This is similar to the vibration magnitudes reported in other mining environments; for example, Aye and Heyns (2011)

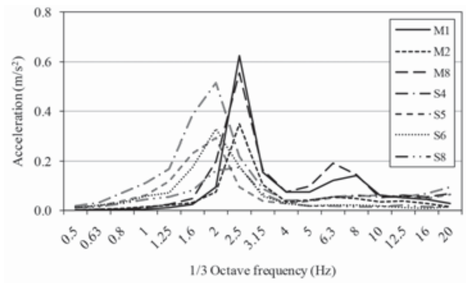

Figure 2—Chassis r.m.s. acceleration data for three LHDs and four skidders at each one-third octave frequency band between 0.5 and 20 Hz. The KAB301 seat performed much better than the CAT seat with LHDs M1, M2, and M8, but the CAT seat performed much better with skidders S4, S5, S6, and S8

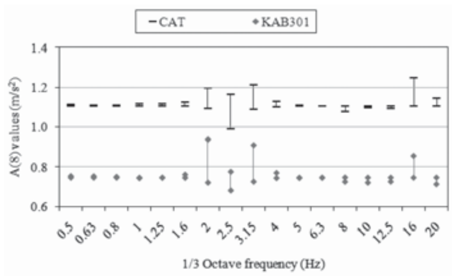

Figure 3—Influence of each vibration frequency band (one-third octave frequency between 0.5 and 20 Hz) on the *A*(8) results for CAT and KAB301 seats for one representative LHD vehicle (M1) in the mining vibration environment. The KAB301 attenuated the vibrations more effectively than the CAT seat for this vehicle. The upper and lower points at each frequency reflect the predicted seatpan *A*(8) magnitudes when the chassis acceleration at that one-third octave band was increased and decreased respectively

reported that approximately 50% of the heavy equipment used in mining causes vibration exposures that exceed exposure action values. Although the vibration exposure for the remaining operator-vehicle combinations did not permit the specific operator-vehicle combinations to be operated for over 8 hours, the KAB301 seat performed better than the other industrial seats (except for near-ties for two vehicles, and for the vehicle where all the seats performed well). These findings are in stark contrast to a parallel study evaluating the effectiveness of these same seats for attenuating vibration exposures in forestry skidder vehicles (Ji, Eger, and Dickey, 2015). We observed that the CAT seat was the best choice for the forestry skidders (between the five seat models that we tested); it limited 96% of the vibrations below the upper limit of the ISO2631-1 HGCZ range. These contrasting findings affirm that seat selection is not universal – the performance and ranking of industrial seats varies between vibration environments. Given that the magnitudes of the vibration total values (a_v) are relatively similar in these two environments (Plewa *et al.*, 2012), it appears that the performance of the seats may depend upon specific features of the vibration environment, such as the frequency spectra. The vibration spectra are different for forestry vehicles and mining vehicles; the dominant frequencies are 2 Hz for the forestry environment and 2.5 Hz for the mining environment (Figure 2). The sensitivity analysis (Figure 3) revealed that the seats had heightened sensitivity for the 2, 2.5, and 3.15 Hz frequency bands. The CAT seat performed better with the forestry vehicles (Ji, Eger, and Dickey, 2015) because the forestry vehicles have dominant 2 Hz vibrations, and higher 3.15 Hz vibrations than the mining vehicles (Figure 2), and the CAT seat was much less sensitive to increases in the magnitude of these two frequency components than the KAB 301 seat (Figure 3). Similarly, the KAB 301 seat performed better with the mining vehicles because the dominant frequency for LHDs was 2.5 Hz (Figure 2), and the KAB 301 seat was less sensitive to this frequency than the CAT seat (Figure 3). Our results are consistent with the previous report (Griffin *et al.*, 2006) that each seat suspension system amplifies the vibration in specific frequency ranges. Seat selection must be optimized by matching the performance of specific industrial seats with the frequency spectra for the vibration environments.

The number of vehicles was rather limited (10 LHDs) and we analysed a relatively small number of industrial seats. However, the seats evaluated were previously identified as the most common type currently used in the underground mining environment in Ontario. Although the current study has identified differences in performance between these five seats, this project is not intended to endorse specific seats – rather, we intend to emphasize the important point that industrial seats must be matched to the specific vibration environment. It is impossible to make universal recommendations about seat selection, as each seat's performance varies depending on the vibration exposure. Given that our study was limited to five seats, it would be helpful to expand our modelling approach to a larger number of seats. We propose to continue efforts to extend our seat selection investigations into other vibration environments, and to evaluate the responses and health risks of heavy machine operators with multi-axis vibrations.

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Appendix

A(8) results and the corresponding working hours to reach the upper limit of the ISO 2631-1 health guidance caution zone (HGCZ) for 8-hour working duration. Values in bold indicate exposures that require more than 8 working hours to access the upper limit of the HGCZ for five industrial seats with different driver anthropometrics (*BMI Primes*) in the forestry vibration environments. Reproduced from Ji, Eger, and Dickey (2015) with permission from the publisher. ◆

Skidders	*BMI*	Access		Amobi		CAT		KAB301		KAB525	
	Prime	*A*(8) m s^{-2}	Hours	*A*(8) m s^{-2}	Hours	*A*(8) m s^{-2}	Hours	*A*(8) m s^{-2}	Hours	*A*(8) m s^{-2}	Hours
S1	0.74	0.80	**10.07**	0.99	6.67	0.68	**13.94**	0.81	**9.96**	0.87	**8.64**
	1.00	0.76	**11.16**	0.90	**8.07**	0.61	**17.43**	0.75	**11.59**	0.83	**9.48**
	1.20	0.73	**12.13**	0.83	9.48	0.55	**21.08**	0.70	**13.13**	0.80	**10.20**
s2	0.74	0.80	**10.01**	0.95	7.20	0.70	**13.32**	0.79	**10.32**	0.88	**8.45**
	1.00	0.76	**11.10**	0.86	**8.81**	0.63	**16.58**	0.73	**12.06**	0.84	**9.26**
	1.20	0.73	**12.07**	0.79	**10.45**	0.57	**19.97**	0.69	**13.71**	0.81	**9.97**
S3	0.74	0.79	**10.46**	0.98	6.73	0.81	**9.81**	0.90	7.96	0.86	**8.74**
	1.00	0.75	**11.62**	0.89	**8.17**	0.74	**11.79**	0.84	**9.12**	0.82	**9.59**
	1.20	0.72	**12.65**	0.82	**9.61**	0.69	**13.75**	0.80	**10.19**	0.79	**10.34**
S4	0.74	1.34	3.60	1.63	2.43	0.97	6.89	1.37	3.44	1.58	2.59
	1.00	1.30	3.83	1.54	2.72	0.90	**8.02**	1.32	3.75	1.54	2.72
	1.20	1.27	4.01	1.48	2.97	0.84	**9.09**	1.27	4.02	1.51	2.83
S5	0.74	1.11	5.28	1.33	3.69	0.86	**8.77**	1.13	5.11	1.30	3.84
	1.00	1.07	5.68	1.24	4.25	0.79	**10.44**	1.07	5.69	1.26	4.08
	1.20	1.04	6.03	1.17	4.77	0.73	**12.07**	1.02	6.20	1.23	4.28
S6	0.74	1.03	6.15	1.30	3.85	0.69	**13.45**	1.08	5.53	1.21	4.43
	1.00	0.99	6.67	1.21	4.46	0.62	**16.77**	1.02	6.19	1.17	4.73
	1.20	0.95	7.11	1.14	5.02	0.57	**20.23**	0.98	6.78	1.14	4.99
S7	0.74	0.87	**8.51**	0.99	6.55	0.77	**11.06**	0.84	**9.16**	0.94	7.29
	1.00	0.83	**9.35**	0.90	7.93	0.69	**13.47**	0.78	**10.60**	0.90	7.93
	1.20	0.80	**10.09**	0.83	**9.30**	0.64	**15.90**	0.74	**11.95**	0.87	**8.49**
S8	0.74	0.94	7.27	1.17	4.77	0.66	**14.85**	0.99	6.66	1.08	5.59
	1.00	0.90	7.94	1.07	5.61	0.59	**18.73**	0.93	7.54	1.04	6.02
	1.20	0.87	**8.52**	1.00	6.42	0.53	**22.86**	0.88	**8.34**	1.01	6.39