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A Comparison of Multiple Machine Learning Algorithms to Predict Whole-Body Vibration Exposure of Dumper Operators in Iron Ore Mines in India

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Abstract: *Background*: This study deals with some factors that influence the exposure of whole-body vibration (WBV) of dumper operators in surface mines. The study also highlights the approach to improve the multivariate linear analysis outcomes when collinearity exists between certain factor pairs.

Material and Methods: A total number of 130 vibration readings was taken from two adjacent surface iron ore mines. The frequency-weighted RMS acceleration was used for the WBV exposure assessment of the dumper operators. The factors considered in this study are age, weight, seat backrest height, awkward posture, the machine age, load tonnage, dumper speed and haul road condition. Four machine learning models were explored through the empirical training-testing approach.

Results: The bootstrap linear regression model was found to be the best model based on performance and predictability when compared to multiple linear regression, LASSO regression, and decision tree. Results revealed that multiple factors influence WBV exposure. The significant factors are: weight of operators (regression coefficient β =-0.005, $p<0.001$), awkward posture (β=0.033, $p<0.001$), load tonnage (β=-0.026, $p<0.05$), dumper speed (β=0.008, $p<0.001$) and poor haul road condition (β=0.015, $p<0.001$).

Conclusion: The bootstrap linear regression model produced efficient results for the dataset which was characterized by collinearity. WBV exposure is multifactorial. Regular monitoring of WBV exposure and corrective actions through appropriate prevention programs including the ergonomic design of the seat would increase the health and safety of operators.

Keywords: Whole-body vibration, occupational health and safety, bootstrapping, collinearity.

1. INTRODUCTION

Mining has been the backbone of industrial and economic growth in all countries. Continuously growing demand for minerals resulted in tremendous pressure on the workforce due to an intensive and rigorous production schedule. This has also affected the machine operators who are fatigued and discomforted by physical work and suffer from occupational health hazards. Exposure to whole-body vibration (WBV) is one of the significant health hazards for the operators [1], which can increase musculoskeletal disorder (MSD) risk, such as low back pain (LBP), shoulder pain, and neck pain [2-8].

Several studies have revealed a high daily exposure to WBV among heavy equipment operators, especially load haul dump (LHD), dozers, drill machines, loaders, and haul trucks' operators [9-12]. A few studies reported that operators, including LHD operators, were exposed to vibration levels that exceeded the health guidance caution zone (HGCZ) vibration limit [9-10]. In an Australian study, drivers in several mining vehicles were studied for health effects due to vibration exposure that exceeded the vibration limit [13]. Mayton *et al*. (2008, 2014) concluded that haul trucks and front-end loaders operators were exposed to WBV above the International Organisation for Standardisation (ISO) limits [11, 14]. The number of workers in India who are exposed to WBV on a regular basis ranges from 0.18 million to 1.8 million, and the health consequences related to WBV exposure are highly prominent among them [15]. An assessment of WBV exposure in a number of opencast mines in India revealed that the heavy earthmoving machinery (HEMM) operators are exposed to WBV exceeding the limits specified in the ISO standards, and consequently, they are at increased health risk [15].

Surface mining is accomplished in several parts, from exploration to design, production, and finally, mine closure. Each part requires a high level of mechanization that includes deployment of HEMM for development, production and ancillary processes. Once the mineral has been excavated from the mine, it needs to be transported to the plant for further

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processing. Transportation in surface mines is usually accomplished through dumpers. The dumpers are the most vibration-producing equipment among all the equipment in mines due to their continuous movement on the irregular, undulated, and rough haul road conditions with constant engine vibration. This results in exposing the operators to multiple shocks and impacts. A few field investigations have reported on WBV exposure for mining haul trucks [11, 16]. Smets *et al*. (2010) reported on a review of Canadian accident statistics for the Ontario Mining Industry, which showed that 16% of the traumatic injuries were associated with haul trucks operation. They concluded that haul truck operator's exposure to WBV posed a significant health risk and the exposure limit recommended in ISO 2631 exceeded for a majority of the exposure time. As operators are exposed to vibration for a considerable duration, they are prone to develop MSD problems [2-8].

In comparison to other heavy earthmoving machinery (HEMMs) in a mine, dumper operators are continuously exposed to WBV and shocks [15]. Dumpers travel long distances in mines to transport materials on irregular and undulated haul road surfaces with limited breaks and their engine run for about 90% of the 8-h shifts. However the WBV exposure studies for HEMMs deployed in mining operations in general and particularly, dumpers are very limited [11, 14-15]. Further, these studies are also limited to small sample size (n=7-11), making the conclusions drawn from the studies inadequate [9, 17]. Therefore, data available to characterize the vibration exposures and to better understand the health risks to dumper operators of the mining industry are insufficient. Consequently, the WBV exposures of dumper operators remain poorly understood, and therefore it needs to be evaluated with greater scrutiny considering a more significant number of operators.

WBV exposure of workers comprises a complex interaction of several parameters. In various studies on WBV exposure of HEMM operators in the mining industry [11, 18-22], several factors have been identified to have an association with the WBV exposure [23-28]. A few studies found that vibration magnitude depended on the particular type of vehicle [25, 28-30]. Other studies found significantly higher vibration values among haul truck operators at a higher speed compared to a lower speed [28, 31]. In these studies, the speed of vehicles was found to be a contributing factor to WBV exposure. Some studies found evidence that personal factors such as age and weight of operators were significant contributing factors to vibration magnitude measured at the seat [32-33]. A few studies have also found evidence of machine-related factors influencing WBV [14, 34]. A study on professional truck drivers had shown that various factors related to machine and operator's features influenced the WBV exposure [18]. In their study, Mayton *et al*. (2014) concluded that the age of haul trucks affects exposure to WBV. In the same study, the authors found a reduction in vibration magnitude with better seat suspension and seat design. Some of the studies found that vibration magnitude also depends on the load characteristics of the vehicle [14, 30]. Based on the above literature review, these factors can broadly be categorized into: (1) personal factors such as driver's age and weight; (2) ergonomics related factors such as awkward posture while driving and seat design; (3) machine-related factors that include age of vehicle and load characteristics of vehicle; and (4) operation-related factors such as dumper's speed, and haul road condition.

Multivariate linear regression is the most commonly used technique to determine the associations between input and outcome variables. In a multivariate regression model, the presence of correlation among input variables can decrease the model's efficiency [35-36]. Studies have shown that the bootstrap technique in such models can minimize the effect of collinearity [37-39]. Another approach is using the Decision Tree (Classification and Regression Tree algorithm-CART). Furthermore, LASSO regression (Least Absolute Shrinkage and Selection Operator regression) was explored. It prevents the overfitting of the regression model to the data when the sample size is small [40-41]. The purpose of Lasso is to minimize the prediction error (variance of the regression model). It sets a constraint on the sum of the absolute values of the model parameters. In order to do so, this method applies a shrinking process where it penalizes the coefficients of the regression variables and brings down some of them to zero. During the variable selection process, the variables that still have a non-zero coefficient after the shrinking process are selected to be part of the model [40].

The paper presents the findings of a study that was focused on determining the WBV exposure of dumper operators and exploring how physical, ergonomical, machine-related, and other operational features may influence the exposure, with a large sample size (n=130) from two iron ore mines in India. The study had two specific objectives. The first objective of this study was to establish a relationship between exposure to WBV and independent factors, namely age, weight, inappropriate seat back-rest height, awkward posture, the machine age, speed of dumper, and haul road condition. The second objective was to select the best model from four machine learning models using the empirical training-testing approach.

2. MATERIALS AND METHODS

2.1. Study Sites

This epidemiological study was carried out over a period of 6 months in two opencast iron ore mines located in the eastern part of India. Both the mines are operated by one company and have similar infrastructure and service facilities which are required for a large mechanized opencast mine with an annual production of more than 10 MT of iron ore. Same occupational safety and health practices were being followed in the mines. The iron ores from the mines are sent to a captive steel plant. Iron ore is extracted from a set of 12 m high and 25 m wide benches through the cyclic drilling-blasting operation. The blasted ore is excavated by shovels or loaders and then loaded onto 100-tonne dumpers for transportation to the beneficiation plant.

2.2. Subjects and Study Design

The study sample included 65 dumper operators who were working in the two mines. Out of all the 70 dumper operators who were employed in the mine, 65 operators willingly participated in this study and they all were healthy based on their medical records. The dumper operators work 300 days a year, six days a week and eight hours a day. The mining company allowed the investigation crew to apprise dumper operators about the study. The dumper operators were requested to execute their typical work schedule which comprised of operating the dumper for an entire shift (8 hours) excluding the rest break of 30-40 minutes.

The study protocol comprised of a face-to-face interview using a questionnaire that included information such as the operator's age, body weight, height, experience, presence of disease, and family size. Machine-related information such as manufacturer/dumper model, dumper age (years), seat height, and seat backrest height was collected from the mines. Measurement of WBV exposure, haul road condition, and speed of dumper were collected in the field at the time of operation. WBV exposure was computed for load and no-load conditions so that the effect of load on WBV exposure can be analyzed. A total number of 130 vibration readings of dumper operators was taken from the two opencast iron ore mines.

2.2.1. Personal Features

Dumper operators who participated in the study were requested to fill up a questionnaire to obtain information on personal factors such as age and weight. All participants were male and aged between 27-59 years. The birth date of an operator was the one mentioned in the identity card.

2.2.2. Machine Features

In this study, operators of 17 dumpers from only one manufacturer and one model were included. All the dumpers were 2-5 years old. It is designed specifically for mining, quarrying and construction applications, and it is very reliable in hauling applications. The maximum gross vehicle weight recorded was 166000 kg. The vehicle's tires were standard with a size specification of 27.00 R49. All the vehicles had mechanical seat suspension. The dumpers transported iron ore to a pit-head crushing plant having a lead distance of 2.5-5.2 km. The overburden was transported by the dumpers up to a distance of 2.0 km and was unloaded to in-pit subgrade dump. Seat pan length, seat height, the width of the seat, seat thickness, seat backrest height, and load tonnage were measured during the field study.

2.2.3. Operation-Related Factors

Most of the iron ore deposits of India are hill-top deposits including the two mines where this study was carried out. As the terrain is hilly, the haul road surfaces in the mines were at an inclination of 6 degrees with sharp turns at regular intervals to overcome the inclination of the haul road. Haul roads in the mines were quite uneven and irregular with the presence of puddles, potholes, debris, and bumps at regular intervals. One of the important mining-related factors for dumper operators is the assessment of haul road conditions on which the dumpers ply as poor haul road conditions result in high-intensity vibration exposure to the operators. Assessment of haul road condition was done by measuring the vibration at the floor of the dumper cabin using a magnetic mounted single-axis accelerometer. For assessing the haul road condition, floor vibration was measured for all the dumpers in the running condition and the speed of the vehicle was measured using the GPS system. The differences between haul road surfaces can be distinguished using the International Roughness Index (IRI), which is the most common way to describe road roughness. IRI is defined as the accumulated suspension stroke in a mathematical car model divided by the distance travelled by the vehicle [42]:

$$\frac{a}{IRI} = 0.16\left(\frac{v}{80}\right)^{\frac{1}{2}}$$

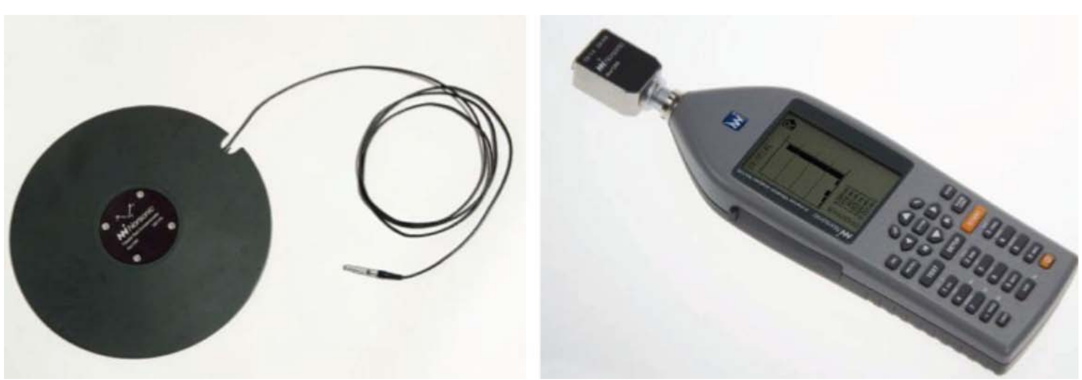
where a is the floor RMS acceleration in the vertical direction and v is the vehicle's speed in km h^{-1}. For different haul roads, using the floor acceleration values, the IRI values were calculated at different velocities and then averaged. The haul road with a rough surface has a higher IRI value, while for the road with a smooth surface, IRI is low. It is expected that poor haul road conditions would result in increasing floor acceleration values. Hence, driving on such haul road surface would cause less comfortable driving.

2.2.4. Measurement of Whole-Body Vibration

A 6-channel vibration meter (Model No.-Nor-136) (Figure **1**) was used to collect the vibration data according to the standard procedure of the ISO 2631-1:1997/Amendment 2010 guidelines. A vibration meter consists of a triaxial accelerometer (Nor 1286) and a 6-channel vibration analyzer. The accelerometer is embedded in a circular seat pad. The seat pad is made up of a rubber pad, an aluminum mounting adapter plate to which the accelerometer is attached. It is hermetically sealed. The triaxial accelerometer meets the ISO 2631 and ISO 8041 requirements for measurement of the WBV exposure. The operating temperature of the accelerometer ranges from -50 to +70 ^{0}C. The accelerometer uses IEPE sensors with a 100-mV/g sensitivity with a supply current of 2-20 mA. It is placed on the seat of the dumper operator to measure vibration that is transmitted to the body (Figure **1**). Vibration data were digitally recorded, time-stamped and stored in the 6-channel vibration analyzer, attached to the accelerometer through a 2m long cable. Numeric and graphical data are displayed on the vibration analyzer screen during and after the measurements.

Vibration was measured about the basicentric axes of the body (Figure **2**). The fore-aft vibration is measured in x-axis, the medial-lateral vibration is measured in y-axis and vibration along the vertical axis is measured in z-axis. Data were transferred to the laptop and analyzed using NorVibraTest post processing software (Nor 1038) after the end of each day's experiment. ISO 2631-1:1997 standard was followed for WBV and shock exposure measurement. Data collection was based on an observational study design. ISO 2631-1:1997 guidelines do not suggest any time period for vibration measurement. However, a number of investigators have preferred the weighted average of three measurements made during the total cycle time as WBV exposure [43]. Our study design comprised of taking WBV exposure data of 6 cycles for each operator as per BS EN 14253:2003 and AI: 2007 (EN 2007) with rest break periods to get a representative WBV exposure of dumper operators for a total exposure duration of 8 hours (daily vibration exposure). A dumper cycle is made up of unit operations such as loading by shovel, loaded travel, unloading and empty travel back to the loading point and a typical cycle time includes waiting time at loading and unloading locations in addition to the time taken for the above operations. Dumper cycle time varied in the range 35-50 min.

Two accelerometers were installed, a monoaxial one near the base of the seat and a tri-axial one on the



(**a**) (**b**)

Figure 1: Six-channel vibration meter No-136: (**a**) Triaxial seat pad accelerometer (Nor1286); (**b**) Six-Channel vibration analyzer (Nor-136).

Figure 2: A dumper operator's seat cabin and seat pad accelerometer with the measurement axes.

seat at the operator/seat interface. Procedures for the cyclical nature of load-haul-dump activities were considered to be representative of exposures for the shift. Measurement periods for dumpers ranged from 30 to 50 min depending on the dumper cycle duration. The Global Positioning Satellite (GPS) data was used to determine the speed of dumpers during loaded and empty travel. The GPS logs with time for each activity were matched with the vibration time histories recorded with the vibration analyzer and WBV exposure were computed for load and no-load condition. Thus, A total of 130 vibration readings were taken for 65 operators operating 17 dumpers in two mines.

2.2.5. Quantification of WBV Exposure

ISO 2631-1:1997 guidelines were followed to assess the health risk from the vibration exposure. The guidelines are applicable to the vibration in the frequency range from 0.5 Hz to 80 Hz, transmitted to the body as a whole through the seat pad. The vibration evaluation procedure incorporates a method of averaging vibration level over time and over frequency band using one-third octave band. For this study, root means square acceleration (RMSA) along all three orthogonal x-, y-, and z-axis was used as the WBV measurements [44]. Total vibration value (vector sum) is the result of vibrations along with three orthogonal directions. Daily exposure A(8) were also calculated to quantify exposure during an 8-hour shift working [45].

RMSA (a_w (ms^{-2})) is calculated using the following expression.

$$a_w = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)dt}.$$

where,

a_w is the RMSA for a time duration T, (m s^{-2})

$a_w(t)$ is the RMSA at a time t, (m s^{-2})

a_{wx}, a_{wy} and a_{wz} are components in the three orthogonal x-, y- and z-axes.

Total vibration, a_{wv} (m s^{-2}), is calculated by the expression given below

$$a_{wv} = \sqrt{(k_x a_{wx})^2 + (k_y a_{wy})^2 + (k_z a_{wz})^2}.$$

In this expression, the multiplying factors (k_x=1.4, k_y=1.4 and k_z=1) account for different damage risks due to WBV exposure along the three axes.

The daily exposure A(8) is estimated from the RMSA in the dominant axis (a_{wz} in the present study) for the time T, using the following expression.

$$A(8) = a_{wz}\sqrt{\frac{T}{8}}.$$

According to ISO 2631-1:1997 guidelines, the upper and lower limits of the health-guidance caution zone for 8 hours exposure, A(8), are 0.9 m s^{-2} and 0.45 m s^{-2}. Also, the value of the frequency weighted RMS acceleration not exceeding ISO lower limit indicates that a worker is at low health risk, between the lower limit and upper limit indicates the worker is at moderate health risk, and above the upper limit makes the worker vulnerable to increased risk of health problems. These exposure levels distinguish the workers who need specific preventive measures. Most of the time, A(8) value is calculated based on the highest value among the three axes which may not be sufficient for certain types of machines or vehicles producing vibration in several axes. In that case, the total vibration exposure should be considered.

2.2.6. Ergonomics Features

Inappropriate Backrest Height

The compatibility of seat design with the operator's body dimension provides a measure of comfort/discomfort to the operators. The sitting height of operators was measured using a Martin-Type anthropometer of Takei Scientific Instruments Co. Ltd. (TK-11242, 2012) with a 1-mm precision. The backrest height of seats of the dumper was measured using a measuring tape. The seat backrest height was matched with an operator's sitting height to assess the compatibility of seat design. The sitting height was more than the backrest height for some of the operators, and it was defined as inappropriate for them.

Posture Assessment

If the operator is working in an awkward posture, in course of time, it creates pressure points in the body, which ultimately degrade the health of the operator. The comfort level of an operator during the operation is determined by body posture [46-48]. Posture assessment comprises of identifying the inappropriate postures taken by the operators while they operate the machine. Posture analysis was carried out with the help of Rapid Upper Limb Assessment (RULA) using ErgoMaster software [49]. RULA was developed to evaluate the exposure of individual workers to ergonomic risk factors associated with MSD. The RULA ergonomic assessment tool considers biomechanical and postural load requirements of job tasks/demands on the neck, trunk and upper extremities. In this study, the operator's movements and postures during several work cycles were observed through videos and photography. The ErgoMaster software allows us to import digital images from a video file. The software includes a database, which enables us to easily save and retrieve the posture score based on the images provided as the input [49].

2.3. Statistical Analysis

In the present study, the parameters that were measured using vibration meter were a_{wx}, a_{wy}, a_{wz}, a_{wv} and A(8). Among these parameters a_{wz} was used as outcome variable as the z axis (vertical axis) is the dominant axis for vibration exposure. The role of some variables to vibration exposure was evaluated in this study through multivariate statistical models. The factors considered in this study are personal factors (age and weight), ergonomics-related factors (backrest height and posture), machine-related factors (age of machine and load tonnage), and operation-related factors (average speed and haul road condition). The bivariate correlation between independent variables was obtained using a Pearson correlation coefficient, as all the factors were continuous. The variance inflation factor (VIF) was also calculated to determine the multicollinearity among the independent variables. Initially, the entire dataset was analyzed by a commonly used multiple linear regression model to establish the association between independent and outcome variables. Later, four models were compared using training- testing approach to determine the best model to analyze the current dataset. All tests were two-sided with a significance level of $p<0.05$. Statistical analyses were performed using SPSS (Version 22; IBM Corp., Armonk, NY) and R (Version 4.0.4; R Foundation for Statistical Computing, Vienna, Austria).

In order to to improve the estimates of multivariate analyses, four models were compared, namely multiple linear regression, LASSO regression, bootstrap multiple linear regression, and CART through the training-testing approach. The entire dataset was divided into two parts: the training dataset and the testing dataset. The training dataset was created by a randomized selection process and consisted of two-third of the data. The testing dataset consisted of the remaining one-third of the data. Models were built using the training dataset and compared using test dataset. R^2, root mean squared error (RMSE), mean squared error (MSE) indices were calculated from testing data to select the best model. High R^2 value and low RMSE and MSE value indicate a better model [50].

3. RESULTS

The vibration exposure characteristics of the dumper operators and characteristics of input independent variables are presented in Table **1**. The results revealed that the dumper operators in two study mines were highly exposed to WBV. The magnitude of RMSA was much greater in z-axis (mean=0.61 ms^{-2} and range=0.40-0.94 ms^{-2}) compared to x-axis (mean=0.25 ms^{-2}, range=0.15-0.44 ms^{-2}) and y-axis (mean=0.24 ms^{-2}, range=0.16-0.40 ms^{-2}). The mean of vector sum a_{wv} was 0.77 ms^{-2} (range=0.51-1.41 ms^{-2}). The health risk was assessed from the 8-h equivalent

Table 1: Characteristics of Variables (n=130)

	Mean (SD)	Median	Skewness	Range	< ISO lower limit[a] (%)	Within ISO limits[a] (%)	> ISO upper limit[a] (%)
RMSA							
a_{wx} (anterior-posterior x-axis), ms^{-2}	0.25 (0.05)	0.24	0.912	0.15-0.44	92.30	7.70	0.00
a_{wx} (medial-lateral y-axis), ms^{-2}	0.24 (0.05)	0.23	0.795	0.16-0.40	96.92	3.08	0.00
a_{wz} (vertical z-axis), ms^{-2}	0.61 (0.10)	0.60	1.06	0.40 –0.94	2.30	97.30	0.40
a_{wv} (total), ms^{-2}	0.77 (0.14)	0.75	1.59	0.51 –1.41	0.00	86.15	13.85
A(8) (daily exposure), ms^{-2}	0.61 (0.10)	0.60	1.06	0.40 –0.94	2.30	97.30	0.40
Personal factors							
Age, year	46.3 (9.68)	48.00	-0.391	27.0 – 60.0			
Weight, kg	76.4 (8.48)	76.00	-0.364	60.0 – 92.0			
Ergonomics-related factors							
Awkward posture (Score)	5.02 (1.10)	5.00	0.467	3-7			
Sitting height, cm	84.1 (4.08)	84.30	-0.143	72.30-94.30			
Machine-related factors							
Dump trucks							
Machine's age, year	3.66 (1.52)	4.34	-0.412	1.51-5.50			
Load tonnage, ton	95.23 (3.5)	95.97	-0.52	86.75-101.15			
Operation-related factors							
Average speed, Km h^{-1}	20.0 (6.37)	20.44	0.940	8.05-52.05			
Poor haul road condition (Score)	8.27 (1.44)	8.20	1.367	5.51 – 14.84			

Abbreviations: SD, standard deviation; n, number of subjects, RMSA, frequency-weighted root mean square acceleration.
[a]ISO 2631-1 Health guidance caution zone (HGCZ) (1997) for RMSA: lower limit = 0.45 ms^{-2}, upper limit = 0.90 ms^{-2}.

RMSA, A(8), according to ISO 2631-1:1997/Amendment 2010 standard. In terms of frequency weighted root mean square acceleration based on A(8) value, the exposure level of 98% of operators exceeded the lower limit (0.45 ms^{-2}) of "Health Guidance Caution Zone" (HGCZ).

The majority of the operators were aged 45 years and more. The mean age was 46.3 years (SD=9.68, range=27-60 years). The mean weight of the operators was 76.4 kg m^{-2} (SD=8.48, range 60-92). The average awkward posture score was 5.02 and the ranges was 3-7. The mean backrest height was 84.1. The age of the machine varied from 2 years to 6 years with mean age of 3.66 (SD=1.52) (Table **1**). Each machine operated 7-8 hours in a shift. The tonnage load of dumpers varied in the range 86.75 - 101.15 tons. The haul road condition was assessed using an International Roughness Index (IRI) which varied in the range of 5.51-14.84, where 5 suggests the road to be comparatively smooth while 15 indicates a poorly graded road. The average score for the haul road condition was 8.27. The average dumper speed was 20.0 km h^{-1} (range: 8.05-52.05).

Table **2** shows the bivariate correlation between the independent variables through Pearson correlation and multicollnearity through VIF. As VIF values indicate, there was no multicollinearity between independent variables in multiple regression, but there was a significant bivariate correlation between some of the independent variables. Awkward posture was correlated with weight ($r=-0.34$, $p<0.05$) and inappropriate backrest height ($r=0.25$, $p<0.001$). Also, the average speed was correlated to weight ($r=-0.29$, $p<0.05$) and awkward posture ($r=0.24$, $p<0.05$). Poor haul road condition was correlated to three independent variables, namely awkward posture ($r=0.19$, $p<0.05$), machine age ($r=-0.22$, $p<0.05$), and average speed ($r=0.35$, $p<0.001$).

Initially, the multiple linear regression model was given a run on the entire dataset (n=130). Table **3** shows the results of multiple linear regression model

Table 2: Variance Inflation Factor and Correlation among Predictor Variables (Pearson Correlation Coefficient)

	VARIANCE INFLATION FACTOR	1	2	3	4	5	6	7	8
AGE (1)	1.08	1.00							
WEIGHT (2)	1.31	0.16	1.00						
INAPPROPRIATE BACKREST HEIGHT (3)	1.17	-0.09	-0.24	1.00					
AWKWARD POSTURE (4)	1.28	0.04	-0.34*	0.25‡	1.00				
MACHINE AGE (5)	1.16	0.16	0.15	-0.06	-0.18	1.00			
LOAD VS NO LOAD (6)	1.08	0.01	0.03	0.01	-0.14	0.01	1.00		
AVERAGE SPEED (7)	1.60	0.08	-0.29*	0.23	0.24*	0.05	0.20	1.00	
POOR HAUL ROAD CONDITION (8)	1.42	-0.05	-0.13	0.14	0.19*	-0.22*	0.04	0.35‡	1.00

*$p \leq 0.05$, †$p \leq 0.01$, ‡$p \leq 0.001$.

on the entire dataset. Vibration exposure (a_{wz}) was associated with weight of operator (adjusted-regression coefficient βa= -0.004, p<0.001, 95% CI: -0.005 to -0.002), awkward posture (βa= 0.032, p<0.001, 95% CI: 0.022 to 0.046), backrest height (βa= 0.029, p<0.05, 95% CI: 0.007 to 0.057), load tonnage (βa= -0.021, p<0.05, 95% CI: -0.041 to -0.001), machine age (βa= -0.008, p<0.05, 95% CI: -0.015 to -0.001), average speed (βa= 0.005, p<0.001, 95% CI: 0.003 to 0.009), and haul road condition (βa= 0.012, p<0.001, 95% CI: 0.022 to 0.047).

For comparison of different models, the entire dataset was divided into training and testing. The training dataset consisted of two-third of the entire data (n=93). The testing dataset consisted of the remaining one-third of the data (n=37). Models were built using the training dataset and compared using the test dataset. Table **4** represents the performance of multiple linear regression, LASSO regression, bootstrap linear regression and CART through R^2, RMSE, and MSE indices obtained using the test dataset as well as the training dataset. Every indices indicated the bootstrap linear regression was the best model to analyze the current dataset compared to the other two models as R^2 was highest (0.737 and 0.710 for testing dataset and training dataset, respectively) and the other two indices were lowest (RMSE: 0.0549 and 0.0571; MSE: 0.0029 and 0.0032) for the model.

Table **5** shows the bootstrap regression coefficient values for each input variables, which were calculated by taking the mean of the coefficients obtained by multiple regression analysis of 5000 bootstrap samples as a further increase in the number of the bootstrap sample did not provide any significant change

Table 3: Association of Various Personal, Ergonomical, Machine and Operational Characteristics with WBV Exposure (n=130): Multivariate Linear Regression Analysis

	Multivariate regression coefficient	95% CI¶	
		Lower limit	Upper limit
Age, years	0.001	-0.003	0.002
Weight, kg	-0.004‡	-0.005	-0.002
Awkward posture	0.032‡	0.022	0.046
Inappropriate backrest height	0.029*	0.007	0.057
Load vs no load	-0.021*	-0.041	-0.001
Machine age, years	-0.008*	-0.015	-0.001
Average speed, km h^{-1}	0.005‡	0.003	0.009
Poor haul road condition	0.012‡	0.022	0.047

¶95%CI: 95% confidence interval.
*$p \leq 0.05$, †$p \leq 0.01$, ‡$p \leq 0.001$.

Table 4: Model Comparison Indices

Comparison indices	Testing (n=37)				Training (n=93)			
	Multiple linear regression	Bootstrap linear regression	Decision tree	LASSO regression	Multiple linear regression	Bootstrap linear regression	Decision tree	LASSO regression
R^2	0.725	0.737	0.566	0.681	0.677	0.710	0.581	0.676
RMSE	0.0566	0.0549	0.0647	0.0881	0.0584	0.0571	0.0633	0.0556
MSE	0.0031	0.0029	0.0041	0.0077	0.0034	0.0032	0.0040	0.0031

Table 5: Association of Various Personal, Ergonomical, Machine and Operational Characteristics with WBV Exposure (Training Data: n=93): Multivariate Bootstrap Linear Regression Estimates

	Bootstrap regression coefficient[||]	95% Bootstrap CI [¶]	
		Lower limit	Upper limit
Age, years	0.001	-0.001	0.002
Weight, kg	-0.005[‡]	-0.005	-0.003
Awkward posture	0.033[‡]	0.022	0.044
Inappropriate backrest height	0.006	-0.023	0.036
Load vs no load	-0.026[*]	-0.047	-0.004
Machine age, years	-0.002	-0.008	0.006
Average speed, km h^{-1}	0.008[‡]	0.005	0.009
Poor haul road condition	0.015[‡]	0.021	0.044

[||]Bootstrap regression coefficients were calculated using 5000 bootstrap samples.
[¶]95%CI: 95% confidence interval (calculated using standard bootstrap confidence interval).
[*]$p\leq0.05$, [†]$p\leq0.01$, [‡]$p\leq0.001$.

(percentage change <1%) in coefficients. The significant independent variables were the following: weight of operator (βa= -0.005, p<0.001, 95% CI: -0.005 to -0.003), awkward posture (βa= 0.033, p<0.001, 95% CI: 0.022 to 0.044), load tonnage (βa= -0.026, p<0.05, 95% CI: -0.047 to -0.004), average speed (βa= 0.008, p<0.001, 95% CI: 0.005 to 0.009), and haul road condition (βa= 0.015, p<0.001, 95% CI: 0.021 to 0.044). The results shown in Table **5** were obtained using the training dataset.

4. DISCUSSION

This study aimed to assess the relationship between independent variables and WBV exposure of dumper operators. An observational field-based approach was used for this study. Four models were compared through the empirical training-testing approach to determine the best model to analyze the data, which was correlated. As studies concerning factors influencing WBV exposure are scarce in the Indian mining sector, this study can provide helpful insight to increase health and safety at the worksite.

The dataset used for this study consists of data from two different iron ore mines. As mentioned already, two mines are situated in the same region and operated by the same management. All workers employed by the mines were from the same area. These conditions ensured that factors related to geological conditions, training schedules, and safety management policies were controlled and considered uniform.

4.1. Selection of Appropriate Model

One of the objectives of this study was to select the best model while dealing with collinearity among independent variables. Four models were chosen for this study based on a literature review of the models' capabilities to handle such datasets. The first model was the multivariate linear regression model, which researchers frequently use to establish associations. Correlated independent variables in multiple linear regression can yield an unreliable estimation [35]. Hence, another three models were explored for this study: a bootstrap multiple linear regression model, LASSO regression, and decision tree (CART).

Bootstrap multiple linear regression was used for its capability of producing more accurate estimates by creating multiple samples and diminishing the effect of collinearity. CART model was chosen because of its inherent ability to deal with complex nonlinear relationships [51]. LASSO regression was chosen because it prevents model overfitting and increases prediction accuracy by eliminating unnecessary predictors [40].

It can be observed that the best predictive model was the bootstrap, a multiple linear regression model, as indicated by all three indices calculated based on testing data. The bootstrap multiple linear regression model showed the highest R^2 (0.74), lowest RMSE (0.054), and lowest MSE (0.002) values. As the R^2 value for the bootstrap multiple linear regression model was much higher (0.74), and RMSE (0.054) and MSE values were much lower compared to other models, the outcome of this model was used to interpret the association between vibration exposure and independent variables. In the past, regression models were mainly adopted to predict WBV exposure [11-12]. The use of other alternative methods is not popular in the WBV literature. Although the statistical theories support that the regression model produces good estimates, other approaches such as decision tree and bootstrap modeling are found suitable in developing predictive models [51].

4.2. Vibration Exposure and Health Risk

The present study demonstrates that approximately 97% of the dumper operators in the iron ore mines in eastern India were exposed to a vibration magnitude that exceeded the ISO lower limit (0.45 m s^{-2}). Therefore, operators in the mines are at elevated health risk due to WBV exposure. The high values of vibration magnitude in the z-axis can be attributed to high dumper speed and the poorly graded and maintained haul roads in the mines. In addition, there were potholes, ruts, and bumps on the haul roads, which augment the increase in the magnitude of vibration. Meanwhile, all the dumpers have mechanical seat suspension systems, which are less effective than pneumatic and magnetorheological semi-active damper suspension systems in attenuating and isolating the vibration transmitted to operators. High vibration exposure in the z-axis has also been reported by studies on railroad locomotives in the United States [27], vehicles on a test track in Canada [52], and haulage trucks in an aggregate stone quarry operation in the United States [14]. Laboratory research conducted by Mayton *et al*. (2006) showed that applying pneumatic-based rheonetic technology might provide heavy vehicles with improved isolation from seat transmitted vibration and result in a subsequent reduction in MSD problems [53].

4.3. Relationship between Individual Factors and Vibration Exposure

The multivariate statistical analyses found statistically significant associations for the weight of the dumper operators with WBV exposure in the dominant axis (a_{wz}), at a level of significance $p \leq 0.05$. It is hypothesized from the above observation that higher weight attenuates the effect of vibration transmission into the body. Other studies have also reported a similar association between weight and vibration [23-24]. A small study about rural agricultural workers also found a negative association between body weight and WBV in the z-axis, but body height had little influence [37-39]. Therefore, the role of weight may be more robust in WBV exposure.

4.4. Relationships between Machine and Operational Related Factors with Vibration Exposure

This study shows that machine age is an important predictor of WBV exposure in multivariate models. The vibration exposure based on frequency-weighted RMS acceleration along the dominant axis shows that the average value of exposure is higher for the new dumpers compared to the old dumpers, which is an unexpected finding through this study. Interactions with the operators also revealed that the front suspension system of the new dumpers is not as effective as old dumpers, and that results in more vibration. In order to investigate this issue, a controlled study was carried out in two new dumpers and two old dumpers (both empty) during the rest-break period of the dumper operators, and the results also revealed the same trend. The results revealed that the operators while driving the new dumpers are experiencing more vibration in terms of frequency-weighted RMS acceleration along the dominant axis. We interviewed several dumper operators randomly about this, and all of them corroborated our findings. Discussion with a few mine officials revealed that the old dumpers were commissioned at mines from the beginning; whereas, the new dumpers were first commissioned in some other mine. After some time, these dumpers were decommissioned there, and brought to these two mines, and assembled here again. This may be the most likely reason for more vibration exposure in new dumpers.

The results show that dumper speed and dumper load were associated with the frequency-weighted RMS acceleration in the dominant axis. The observations are similar to some earlier studies, which suggested that driving speed was positively related to the vibration magnitude of operators of highway trucks, forklift trucks, tractors, and dumpers [17, 25, 28, 31]. Vibration exposure in the dominant axis was negatively associated with the load on the dumper.

For the dumpers, the operators sometimes have to bend forward to clearly see the path ahead. This causes improper sitting posture for the operators resulting in increased health risk of lower back pain problems. It is suggested that while planning for acquisitions of new machines, proper attention has to be given to the ergonomical design of the machines. Specifically, when procuring new machines, attention has to be given to several aspects, including the operator's seating comfort, seat dimensions, and seat suspension. For designing further studies on machine models, the transmissibility and the worker's posture may also have to be investigated.

Our study reveals attenuating effects of seat backrest height in vibration transmission to dumper operators in an uncontrolled work environment. These results highlight that it is important to choose appropriate dumpers, which are well designed and constructed by a manufacturer that uses suitable materials and carries out better assemblage. Several studies observed a reduction in vibration magnitude for drivers by using proper seat design in various vehicles such as tractors and trucks [54]. Prevention to limit the WBV exposure should consider the seat design and seat suspension system of dumpers.

4.5. Relationship between Haul Road Condition and Vibration Exposure

There are high variabilities of haul roads in an actual working situation in terms of the presence of potholes, joints, cracks, ruts, spillage, bumps, and fissures. Our study reveals that haul road conditions are strongly associated with WBV. In fact, poor and less graded haul roads contribute more to the magnitude of vibration than operators' experience. Interaction with the operators revealed that as the terrain is hilly, the haul road surfaces in the mines are at an inclination of 6 degrees with sharp turns at regular intervals to overcome the inclination of the haul road. Haul roads in the mines were quite uneven and irregular, which influenced the WBV exposure. Our finding that haul road condition is a potential predictor of WBV in multivariate analyses reflects this phenomenon. Several other studies on WBV exposure are in agreement with the results of our study [11, 34].

4.6. Occupational Implications

The findings of this study may help in identifying the factors that influence the WBV exposure among the dumper operators. Our study shows that the weight of operators is a predictor variable for the WBV exposure among dumper operators. The dumper operators who are exposed to high WBV may need more health surveillance, especially for MSDs and back pain, by the occupational ergonomists and managers. They should be made more aware of the health risks associated with taking risky and awkward postures. They should also be encouraged to pay more attention to their health disorders through regular checkups.

Our research further sheds light on the fact that the WBV exposure is associated with the machine's age, average vehicle speed, load tonnage, and haul road condition. The WBV exposure magnitude for dumper operators can be predominantly high depending on the machine and operation-related factors. In this case, the machine, ergonomics, and operation-related features should be appropriately preferred to reduce the WBV exposure. The ergonomical principles should be followed in designing the dumpers to reduce and control the WBV exposure. Specific attention should be given to aged operators and the operators who are underweight. Our outcomes may thus help in identifying occupational risk factors and executing appropriate prevention and intervention to reduce the risk.

4.7. Limitations

This study also has some limitations. Firstly, it was an observational study, which limits the deduction regarding the cause-effect associations. Our study could not measure the WBV level experienced by the dumper operators encompassing all the seasons. The role of other machine-related factors such as piston pressure and engine firing pressure, which may have influenced WBV, could not be assessed, as it was an observational study design. Job duration was also not investigated in this study. All participants were male since no female operators were available in the study mines. The number of participants was relatively small for an epidemiological study. All study mines belonged to the same company and were from the same geographical region, which greatly facilitated the study.

5. CONCLUSIONS

An empirical training-testing approach was used to choose the best model from the four models explored in this study. The bootstrap regression model was found to be the best for the dataset. In spite of the study being based on a sample with few correlated independent variable pairs, the study of multiple models with the training-testing approach helped to provide reasonable estimates. Also, this study evaluated the association of individual factors, ergonomics-related, machine-related, and operation-related factors with WBV exposure, which is absent in previous studies. Though the estimates cannot be generalized, it is valid for the targeted population and can be used as a base for WBV exposure study in other mines.

The current study concludes that dumper operators in Indian iron ore mines are exposed to levels of vibration above the limit values specified in ISO 2631-1:1997 guidelines. They are also exposed to the high shock component of the vibration. Based on the daily RMSA, 97% of the dumper operators were above the potential health risk values and may require to be monitored regularly. The seat design, awkward posture, vehicle speed, and haul road conditions are significant contributors to WBV exposure. The weight of an operator also plays a role in WBV exposure. Proper machine design is necessary to reduce harmful WBV exposure. The findings of the study have the following salient recommendations: (1) improvement of the seat design that includes an effective seat suspension system and adjustable seat height, with lumbar support; (2) introduction of the latest machines which can overcome difficult haul road conditions; (3) development of ergonomical and participative approaches to limit prolonged sitting of the operators; and (4) job rotation of the operators to operate other mining equipment which has less WBV exposure. During the planning stage of the acquisition of new equipment, the anthropometric data of the operators should be considered for the ergonomic design of the seat. The administration should take appropriate steps to make the dumper operators more aware of the health effects related to vibration exposure and to improve their physical fitness to reduce the chance of MSDs. Factors influencing WBV exposure related to the mining sector in India are hardly documented [12]. It is therefore of considerable importance to develop an adequate database of WBV covering a wide range of operators for Indian mines where working conditions are different from other parts of the world. Our findings are an additional piece to the literature about the WBV exposure in the mining industry as available studies are scarce and would not simultaneously investigate the role of the individual, machine, and ergonomics-related factors.

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CONFLICT OF INTEREST

There were no conflict of interest.

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