

Assessment of whole-body vibrations in dumper operators in eastern India

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ABSTRACT

In the opencast mines, dumper operators usually suffer from Whole Body Vibration (WBV) exposure. Dumpers used in the opencast mines for the production of raw minerals produce a high intensity of vibrations, which are transmitted throughout the body of the worker from vibrating surfaces. WBV exposure levels correlate with escalating health risks for operators, classified by ISO 2631-1:1997 (International Organization for Standardization (ISO), 1997) into low, moderate, and high categories based on daily Root Mean Squared (RMS) acceleration A(8) or Vibration Dose Value VDV (8). The health impact include fatigue, motion sickness, prolonged exposure increases the deterioration of the nervous system, circulatory system, digestive system of the worker. These risks manifest progressively from discomfort to chronic disorders, especially low back pain and spinal issues in mining contexts.

The main aim of the project is to measure the WBV exposure of various dumper operators in opencast mines in India and to study how machine condition, haul road condition, operational culture and personal factors influence vibration exposure of mine operators in an opencast mine. The triaxial accelerometer instrument was mounted on the seat pan of the dumper, for which the WBV was to be measured, and the operator was asked to sit over the instrument properly as described in ISO 2631-1:1997 (ISO, 1997). Then, by following the ISO 2631-1:1997 (ISO, 1997) standards, RMS and VDV were measured. The instrument used for the measurement of WBV was SV 106A.

A total of 45 dumper operators were selected from an opencast iron ore mine in eastern India. It was found that for RMS measurement, about 82.2 per cent of the operators were exposed to WBV between the Exposure Action Value and Exposure Limit Value. For VDV, 20 per cent operators exceeded the Exposure limit value. Using Pearson correlation and multivariate regression analysis, it is concluded that the age of the machine has a strong correlation with the WBV.

INTRODUCTION

To meet the exponential energy and minerals demand, the mining industry has pivoted toward large-scale mechanisation using Heavy Earth Moving Machinery (HEMM). This vital shift from labour-intensive methods to high-capacity equipment optimises mineral extraction, boosts productivity, and ensures a seamless raw material supply to various industries. However, this transition has also intensified occupational health concerns, particularly for operators of HEMM. Among these concerns, Whole Body Vibration (WBV) exposure represents a critical occupational hazard, especially for dumper operators who are subjected to continuous dynamic loading due to machine operation and haul road conditions.

Vibration occurs when a machine oscillates due to internal or external forces, transmitting these oscillations to the human body via the contact point with the vibrating surface. This can happen through machinery handles, known as hand-arm vibration, or through the seat, floor, or any supporting surface of mobile equipment, referred to as whole-body vibration. Operators of HEMMs in opencast mines, such as motor graders, dozers, cranes, dumpers, excavators, and large-diameter drill machines, are subjected to high levels of WBV during their regular operations (Chaudhary *et al*, 2015; Mandal *et al*, 2018; Kaviraj and Kumaraswamidhas, 2018; Kumar *et al*, 2022). If the exposure surpasses the threshold limits established by ISO standards (ISO 2631-1:1997 (ISO, 1997); ISO

2631-5:2004 (ISO, 2004)) and the duration of exposure is sufficiently prolonged, operators may begin to exhibit serious health issues if appropriate precautions are not implemented.

WBV exposure has been strongly associated with adverse health outcomes, including development of sciatic discomfort, lower back pain, and lumbar spine degeneration, which includes intervertebral disc diseases (Tekin, 2022; Upadhyay *et al*, 2025). Atal *et al* (2022) concluded that the aged workers and those with longer exposure had a higher likelihood of lower back pain and elevated blood pressure. Kumar, Aruna and Govinda Raj (2020) found that the major proportion of the measured exposure in dozer operators exceeded ISO 2631-1:1997 (ISO, 1997) Health Guidance Caution Zone (HGCZ). These health conditions can lead to increased sick leave, temporary or minor disabilities, and significant man-days lost in mining operations.

The severity of health effects due to WBV exposure depends on several factors, including the operator's age, weight, seat posture, the age of the machinery, load tonnage, dumper speed, haul road condition, vibration intensity, vibration frequency, intra-body motion distribution, vibration direction, and exposure duration (Upadhyay *et al*, 2021). Each of these factors are vital in assessing the health risks linked to WBV. In this study an attempt is made to evaluate the WBV exposure experienced by dumper operators in an opencast mine in Eastern India and to develop a predictive model for estimating WBV exposure.

METHODOLOGY

Study area and sample selection

The study was conducted in an opencast iron ore mine located in Eastern India, where shovel-dumper combination is used for loading and material transportation respectively. A representative sample of dumper operators and machines was selected to capture variability in operational conditions.

A total of nine dumpers (two Komatsu, four Caterpillar and three BEML) were included in the study. The age of the machine showed variation from 4–15 years. The average seat pad thickness is 10 cm. The Komatsu dumpers had a power of 1200 HP, the Caterpillar dumper has a power of 938 HP, and the BEML dumpers had a power of 746 HP. The capacity of all the dumpers are 100 tons.

Operator-specific information such as age, experience, weight, smoking, alcohol consumption, health condition, type of health issue was also recorded from 45 dumper operators to examine their potential influence on WBV exposure.

Instrument and data acquisition

Operator-specific information was collected using a questionnaire. WBV measurements were conducted using a SV106A instrument in conjunction with a triaxial accelerometer seat pad, capable of recording vibration signals along three orthogonal axes (x, y, and z). The triaxial accelerometer seat pad is placed at the seat-operator interface, and the driver is instructed to sit on it while operating the HEMM (Figure 1).

The guidelines set forth in ISO 2631-1:1997 (ISO, 1997) were adhered to during the entire process. The recorded acceleration signals were frequency-weighted using appropriate weighting factors (W_k for vertical axis and W_d for horizontal axes), as prescribed by the standard. Measurements are recorded on the operational machine for a duration of 20–30 mins for each individual machine. The WBV measurements for all the dumpers were made along the same haul road and at when the dumper speed is of 35 km per hr.



FIG 1 – SV106A human vibration metre and seat pad accelerometer.

WBV exposure assessment metrics

WBV exposure was quantified using two primary indices as per ISO 2631-1:1997 (ISO, 1997):

1. Daily Exposure Value A(8)
2. Vibration Dose Value (VDV)

Daily Exposure Value A(8)

The A(8) value represents the frequency weighted root mean square (RMS) acceleration normalised to an 8-hour reference period. It is calculated as:

$$A(8) = a_w \sqrt{\frac{T}{T_0}}$$

Where:

- a_w is the vibration magnitude (in m/s^2) on the axis which measured highest, including the weighting factor, $k=1.4$, for the x and y axes
- T is the actual duration in hours of exposure to the vibration magnitude a_w
- T_0 is the reference duration of eight hrs

Vibration Dose Value (VDV)

VDV is calculated as the root mean quad of the acceleration and is more sensitive to peaks in acceleration than the RMS acceleration. This gives a result in $m/s^{1.75}$. Weighting factors of 1.4 apply on the x and y axes. The VDV considers the transient shocks and impulsive vibrations. It is calculated as:

$$VDV = \left(\int_0^T a^4(t) dt \right)^{1/4}$$

Where:

- $a(t)$ is the frequency weighted acceleration

The VDV for eight hrs can be worked out for each axis as:

$$VDV_{8h} = VDV_{measured} \times \left(\frac{T_{ref}}{T_{measured}} \right)^{1/4}$$

Where:

- T_{ref} is the daily duration of exposure

- $VDV_{measured}$ is the VDV value measured along a specific axis

$T_{measured}$ is the duration during which the VDV was recorded

The calculated A(8) and VDV values were compared against the EU 2002/44/EC vibration Directive-defined Exposure Values shown in Table 1 (European Parliament and of the Council, 2002).

TABLE 1
WBV exposure limits for the eight hrs working conditions.

Parameter	Exposure action value	Exposure limit value	Units
A(8)	0.5	1.15	m/s ²
VDV	9.1	21	m/s ^{1.75}

Statistical analysis

To investigate the relationship between WBV exposure and influencing factors, two techniques were used:

1. Pearson Correlation Analysis.
2. Multivariate Regression Modelling.

To assess the individual strength and direction of correlation between the risk factors and the vibration intensity, the Pearson Correlation coefficient (r) was computed. A p-value was determined for each of these correlations. If the p-value is less than 0.05, the relationship is deemed significant and not due to random chance. If the p-value is less than 0.09, the relationship is considered nearly significant.

In order to consider the concurrent effects of various factors, a multivariate regression model was developed. This model utilises the ordinary least squares method, which aims to identify the best-fitting line by minimising the sum of squared residuals (the difference between the actual and estimated vibration values). The effectiveness of the model was evaluated using the adjusted R-squared value. All the computations were performed using the pandas and NumPy libraries of the Python programming language, and the regression model was built using the statsmodels package of the Python programming language.

RESULTS AND DISCUSSIONS

The WBV exposure levels recorded for dumper operators are presented in Table 2. The exposure levels were systematically analysed in accordance with EU 2002/44/EC vibration Directive (European Parliament and of the Council, 2002). As the crest factor is >9, VDV is also considered along with A(8) for evaluation.

TABLE 2
WBV exposure measured for dumper operators in opencast iron ore mine.

Operator #	Age (year)	Experience (year)	Weight (kg)	Smoking habit	Drinking habit	Health issue	Make	Age of machine (year)	A(8) in m/s ²	VDV(m/s ^{1.75})
1	40	8	71	Yes	Yes	-	Komatsu	15	0.91	21.1
2	55	16	82	No	No	-	BEML	4	0.42	8.9
3	48	10	58	No	Yes	pain in neck	BEML	4	0.52	10.5
4	48	10	58	No	Yes	-	Caterpillar	4	0.53	10.5
5	45	11	74	Yes	Yes	-	Komatsu	14	0.79	18.3
6	54	15	71	Yes	No	lower back pain	Komatsu	4	0.52	10.0

Operator #	Age (year)	Experience (year)	Weight (kg)	Smoking habit	Drinking habit	Health issue	Make	Age of machine (year)	A(8) in m/s ²	VDV(m/s ^{1.75})
7	40	8	72	Yes	Yes	lower back pain	BEML	15	0.93	21.0
8	48	10	57	Yes	Yes	pain in neck	Caterpillar	4	0.55	10.1
9	55	15	81	No	Yes	pain in back	Komatsu	4	0.44	9.1
10	36	7	52	No	No	-	BEML	15	0.93	22.3
11	52	12	64	No	No	-	Caterpillar	9	0.85	15.7
12	55	16	82	No	No	-	Komatsu	4	0.42	9.7
13	47	10	58	Yes	Yes	-	BEML	4	0.55	10.1
14	45	11	75	No	No	lower back pain	BEML	13	0.78	18.6
15	36	4	55	Yes	Yes	-	Komatsu	15	0.93	21.5
16	36	4	55	No	Yes	pain in arms	Komatsu	15	0.95	21.1
17	39	7	62	Yes	No	pain in back	Komatsu	4	0.44	10.8
18	49	14	62	No	No	pain in back	Caterpillar	9	0.72	16.6
19	45	11	75	No	Yes	-	BEML	13	0.80	18.4
20	54	20	79	Yes	Yes	-	Caterpillar	9	0.91	15.7
21	47	10	50	Yes	No	-	Caterpillar	13	0.80	16.2
22	54	15	71	No	Yes	-	Caterpillar	4	0.52	10.4
23	37	7	53	Yes	No	pain in back	Caterpillar	15	0.93	22.5
24	48	8	56	No	Yes	-	Caterpillar	9	0.95	16.1
25	45	10	74	No	Yes	-	Caterpillar	13	0.80	18.3
26	36	7	53	No	No	pain in shoulder	Komatsu	15	0.93	22.5
27	48	10	58	No	No	-	Caterpillar	4	0.54	10.6
28	39	7	61	No	Yes	pain in arms	Komatsu	4	0.42	10.6
29	39	7	62	No	No	pain in shoulder	Caterpillar	4	0.43	10.2
30	47	10	63	Yes	No	pain in neck	BEML	9	0.91	17.2
31	57	13	67	Yes	No	-	BEML	15	0.88	19.4
32	36	4	55	Yes	Yes	pain in neck	Komatsu	15	0.93	21.5
33	45	11	74	No	No	pain in neck	BEML	13	0.76	18.7
34	47	8	57	No	No	pain in arms	BEML	9	0.91	15.8
35	50	14	70	No	Yes	-	Komatsu	4	0.60	9.9
36	57	13	68	No	No	-	BEML	15	0.90	19.5
37	47	10	50	No	No	pain in arms	Komatsu	13	0.77	16.0
38	48	8	57	Yes	Yes	lower back pain	Komatsu	9	0.91	16.1
39	46	9	71	Yes	Yes	pain in shoulder	BEML	4	0.38	8.9
40	48	14	62	No	Yes	-	Caterpillar	9	0.75	16.1
41	36	4	55	No	Yes	pain in shoulder	Komatsu	15	0.94	21.7
42	47	10	63	No	No	pain in arms	Komatsu	9	0.90	17.2
43	39	7	63	No	No	pain in shoulder	Caterpillar	4	0.43	10.4
44	47	10	62	Yes	Yes	lower back pain	Caterpillar	9	0.91	17.2
45	36	7	53	No	No	pain in back	Komatsu	15	0.92	22.2

From Table 2, it can be observed that as per A(8), around 17.8 per cent of operators are within safe limits and rest others are in between exposure action value and exposure limit value. As per VDV, around 6.7 per cent are within safe limits, 73.3 per cent are between exposure action value and exposure limit value, and 20 per cent of operators are exposed to vibration levels greater than exposure limit value.

A key observation from the measurements is that WBV exposure is consistently higher along the vertical (z-axis) compared to the longitudinal (x-axis) and lateral (y-axis) directions. This suggests that vertical shock transmission, primarily arising from haul road conditions and vehicle suspension characteristics, is the dominant contributor to operator exposure.

Pearson correlation analysis was conducted to evaluate relationships between risk factors and WBV exposure metrics in dumper operators as shown in Table 3. The analysis reveals that the age of the dumper shows a strong positive correlation with both A(8) and VDV, with statistically significant p-values ($p < 0.05$). Other variables, including operator age, weight, and experience, exhibit weak or statistically insignificant correlations. This indicates that the machine-related parameters dominate over operator related characteristics in influencing WBV exposure levels.

TABLE 3

Pearson correlation of risk factors to outcome variables for dumper operators.

Factor	Correlation with A(8)	Correlation with VDV	A(8) (p-value)	VDV (p-value)
Age	-0.294	-0.501	0.191	0.039
Weight	-0.337	-0.309	0.021	0.165
Experience	-0.313	-0.438	0.917	0.231
Age of machine	0.864	0.968	$1.072e^{-05}$	$2.039e^{-11}$

A multivariate linear regression model was developed to predict WBV exposure among the dumper operators as shown in Table 4. From the Table 4, it can be seen that the age of the machine is the most significant predictor of WBV exposure for both A(8) and VDV.

TABLE 4

Multivariate regression model for dumper operators.

	A(8)			VDV		
	Coefficients	Standard Error	P-value	Coefficients	Standard Error	P-value
Intercept	0.41	0.20	0.530	13.09	2.35	<0.001
Age	0.01	0.00	0.190	-0.12	0.05	0.039
Weight	-0.01	0.00	0.020	-0.04	0.03	0.165
Experience	0.00	0.01	0.905	0.13	0.11	0.235
Age of the machine	0.04	0.00	<0.001	0.93	0.04	<0.001
Adjusted R-squared		0.77			0.94	
RMSE		0.1			1.09	

For the A(8) model, weight of the operator exhibits a statistically significant negative association ($p = 0.02$), suggesting that higher body mass may contribute to marginal attenuation of transmitted vibration, possibly due to damping effects. However, operator age and experience do not show statistically significant contributions ($p > 0.05$), indicating limited direct influence on daily vibration exposure when machine-related factors are accounted for. In contrast, the VDV, identified operator age as a significant predictor ($\beta = -0.12$, $p = 0.039$). Other variables, including weight and experience, do not exhibit statistically significant effects.

The models demonstrated strong explanatory capability, with adjusted R^2 values of 0.77 for A(8) and 0.94 for VDV, indicating that the selected predictors account for a substantial proportion of variability in WBV exposure. Additionally, the relatively low RMSE values (0.10 for A(8) and 1.09 for VDV) confirm the robustness and predictive reliability of the regression models.

CONCLUSIONS

This study provides a comprehensive assessment of WBV exposure among dumper operators in an opencast iron ore mine in Eastern India. The findings clearly indicate that a significant proportion of operators are exposed to vibration levels exceeding EU Directive-recommended thresholds, thereby posing considerable occupational health risks. The main conclusions of the study are as follows:

- Vertical vibration (z-axis) constitutes the dominant exposure component.
- WBV exposure is predominantly governed by machine-related factors, particularly the age of the dumper, which emerged as the most significant predictor across all statistical analyses.
- The developed multivariate regression models demonstrate strong predictive capability, enabling reliable estimation of WBV exposure for operational planning and risk mitigation.
- A considerable proportion of operators reported musculoskeletal disorders, indicating the long-term health implications of sustained WBV exposure.
- Lifestyle factors such as smoking and alcohol consumption show observable trends but limited statistical significance, suggesting that occupational exposure remains the primary driver of risk.

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