Predictors of Whole-Body Vibration Exposure among Indian Bus and Truck Drivers

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Abstract. Heavy vehicle drivers in the Indian road transport industry are generally exposed to whole-body vibration (WBV) and shock loading resulting in musculoskeletal disorders (MSDs) in their different body parts. Not much work has been done in identifying the contribution of driver's personal and vehicle/road-related factors in the enhancement of vibration and shock exposure. This study has been conducted on 10 bus and 10 truck drivers from Northern India to investigate the role of these factors. Based on previous studies, the factors or predictor variables included were driver’s age, body mass index (BMI), driving experience, age of vehicle, mileage, age of tyres, and seat pad thickness. 8-hours vector sum acceleration, i.e., \( \text{A}(8)_s \) and vibration dose value, i.e., \( \text{VDV}(8)_s \) of 25% of the drivers were found to be more than upper limit values of ISO 2631-1. The WBV exposure magnitudes of acceleration and vibration dose value were much higher along the vertical z-axis than along the longitudinal x-axis and lateral y-axis. The results of univariate linear regression analysis found both vibrations and shocks to be related to the driver’s age, body mass index (BMI), driving experience, vehicle speed, and road roughness. Similar types of results were observed from multiple regression analyses with the only exception that no association was found between BMI and WBV exposure in this case. The results of the study may help the authorities in minimising the risks associated with the driver's profession.

Keywords: Whole-body vibration, Vehicle drivers, Predictors, Frequency-weighted root mean square acceleration, Vibration dose value

1. Introduction

Professional bus and truck drivers are generally exposed to continuous vibrations for prolonged periods [1]. These vibrations enter the driver’s body through the seat-body interface, hands, and feet. The health issues related to vibration exposure are more common in bus and truck drivers as they are normally more exposed and therefore suffer more from work-related musculoskeletal disorders than the rest of the population [2, 3]. Numerous studies have been carried out in the recent past to identify the roles of various factors associated with WBV exposure in different types of transport vehicles and mining equipment.
In a study on car drivers, a new seat design was able to reduce both contact pressure and vibration amplitude at the driver's seat. Root-mean-square (RMS) acceleration and vibration dose value (VDV) in the vertical direction of the lumbar spine decreased by 31.6% and 43% respectively [4]. A study on bus drivers investigated the role of different types of seats on different types of roads and it was found that city streets and older road segments had the highest WBV exposure levels [5]. A study was conducted on forklift drivers and its results showed that a combination of a new driving surface, speed reduction, and the use of an air suspension seat reduced the WBV exposure below the action limit [6]. A study conducted on drivers of suspended cabin tractor semitrailers in India concluded that the WBV exposure levels on the rough roads were higher than on the smooth roads and the WBV experienced by the drivers increased with vehicle speed on all types of roads [7]. A study conducted to compare the WBV levels in the high-floor coach bus and the low-floor bus, showed that the vibration exposures were significantly different for different types of rods. The WBV magnitudes were highest on the speed breakers and lowest on the smooth freeways [8]. A study on drill operators in India found that various risk factors associated with WBV exposure were: age of operator, machine manufacturer, age of drill, hardness uni-axial compressive strength, and density of rock [9]. From the results of these studies, it may be observed that vehicle design, vehicle speed, seat design, seat suspension, and type of road are related to WBV exposures. However, there are not many studies available on factors affecting WBV exposure in bus and truck drivers in India. The present study has been conducted with the aim to characterize WBV exposures in Indian bus and truck drivers and determine whether there were some other factors like driver's age, body mass index (BMI), driving experience, vehicle age, mileage, age of tyres, and seat pad thickness that may affect WBV exposures.

2. Materials and Methods

2.1. Study Design

The study involved 10 bus and 10 truck drivers from northern India. Drivers were selected based on their willingness to be associated with the study. The purpose of the study and the associated risks/benefits were explained to the subjects in their local language. Voluntary consent for participation was followed in selecting the study subjects. All the drivers were full-time professional drivers and no part-time driver was involved in the study. All the drivers had complete knowledge about the route and none of them was driving the vehicle first time on that route. The study route consisted of a smooth state highway and a rough village road. The individual data of drivers were collected by using an interviewer-administered questionnaire. Personal factors like driver’s age, stature, weight, and, number of years in the driving profession were included in the questionnaire. The vehicle-related data (age of vehicle and age of tyres) were collected through registration and service records. Vehicle mileage was recorded from the vehicle odometer at the starting of the trip. Seat pad thickness was measured during the field study.

2.2. Personal Characteristics of the Drivers

All 20 participating drivers were males aged 23-52 years with an average age of 37.8±10.2 years. The standing weight and standing height of each driver were measured to calculate his BMI. The average BMI was 24.8±2.8 kg/m² (range19.9-29.2 kg/m²). The maximum value of BMI was 29.2 which indicated that no driver was obese. The average driving experience was 14.8±9.8 years (range 2-31 years) (Table. 1).

2.3. Vehicle and Road Related Factors

The average age of vehicles was 7.1±1.6 years (range 3.8-9.4 years). The average vehicle mileage was 104078±26706 km (range 54378-136548 km). The age of tyres was 0.4-4.5 years with a mean age of 3±1.3 years. Seat pad thickness had a narrow range (9.1-10) cm with a mean of 9.5±0.3 cm. The speed
of the vehicle was noted during WBV measurement. The speed ranged between 20-60 kilometer per hour (km/h) with an average speed of 46.2±11.6 km/h.

2.4. Measurement of Whole-Body Vibration

WBV measurements were made based on an observational study design. In this type of design, study organisers do not have any control over study participants and study variables. A 3-channel-vibration meter was used for measuring triaxial vibration values on the driver’s seat. The vibration meter had a tri-axial accelerometer and a 3-channel-vibration analyzer. Accelerometer was mounted in a circular seat pad. This pad was placed on driver’s seat and the driver was asked to sit on top of it. Accelerometer outputs were acquired by the vibration analyzer. WBV measurements were made along the basicaentric axes with the x-axis measuring longitudinal vibration, the y-axis measuring transverse vibration, and the z-axis measuring vertical vibration [10].

2.5. WBV Evaluation as per ISO 2631 Standards

The whole-body vibration measurements included estimations of root mean square (RMS) acceleration, vibration dose value (VDV), and crest factor (CF) along three mutually perpendicular (x, y, and z) axes [11]. Root mean square (RMS) weighted average acceleration \( a_w \) calculated at the seat pan (m/s²):

\[
a_w = \left[ \frac{1}{T} \int_0^T a_w(t) \, dt \right]^{\frac{1}{2}}
\]  

(1)

where \( a_w(t) \) is the instantaneous frequency-weighted acceleration at time \( t \) and \( T \) is the duration of RMS acceleration, in seconds.

The vibration total value (or vector sum) of the weighted RMS accelerations \( a_{ws} \) (m/s²) is defined as:

\[
a_{ws} = \left[ (1 \cdot 4a_{wx})^2 + (1 \cdot 4a_{wy})^2 + a_{wz}^2 \right]^{\frac{1}{2}}
\]  

(2)

Here, the multiplying factors 1.4 in x and y directions and 1 in the z-direction, represent damage risks associated with WBV exposure along the orthogonal axes [11, 12].

The vector sum and dominant z-axis values of daily exposure \( A(8) \) are estimated from the vector sum acceleration \( a_{ws} \) and RMS acceleration in dominant z-axis \( a_{wz} \):

\[
A(8)_x = a_{ws} (T/8)^{\frac{1}{2}}
\]  

(3)

\[
A(8)_z = a_{wz} (T/8)^{\frac{1}{2}}
\]  

(4)

The vibration dose value is more suitable in case of impulsive vibration and represents the aggregate, on contrary to average vibration, over the measurement period [11, 13]. VDV (m/s\(^{1.75}\)) is defined by:
Total VDV or vector sum VDV, $VDV_s$ (m/s$^{1.75}$), is defined in the same way as vector sum acceleration $a_{ws}$ in equation (2):

$$ VDV_s = \left[ (1.4 VDV_{x})^4 + (1.4 VDV_{y})^4 + VDV_{z}^4 \right]^{\frac{1}{4}} $$

(6)

To obtain VDV equivalent to 8 hours for vector sum and z-axis, the following equations were used:

$$ VDV(8)_s = VDV_s \left( \frac{8}{T_m} \right)^{\frac{1}{4}} $$

(7)

$$ VDV(8)_z = VDV_z \left( \frac{8}{T_m} \right)^{\frac{1}{4}} $$

(8)

where $T_m$ represents the time duration of each measurement.

The crest factor (CF) measures the shock component of WBV. It is defined as the ratio of the highest value of $a_w(t)$ over time $T$ and the value of $a_w$ [14]. When the value of CF is more than 9, the fourth power averaging approach (root-mean-quad) is considered more suitable to assess potential negative health effects [15].

2.6. Health Risk Assessment of Bus and Truck Drivers

WBV health risk assessment of drivers was carried out as per ISO 2631- 1:1997 Standards. The vector sum and predominant z-axis $A(8)$ values were used to assess the daily vibration exposure. The value of $A(8)$ less than 0.45 was considered as low health risk, between 0.45 and 0.9 as moderate health risk, and above 0.9 as high health risk. The vector sum and predominant z-axis $VDV(8)$ values were used to assess the risks caused due to transient vibration and repetitive shocks. The value of $A(8)$ less than 8.5 was considered as low health risk, between 8.5 and 17 as moderate health risk, and above 17 as high health risk.

2.7. Statistical Analysis

The collected data were analyzed with the help of SPSS for Windows version 22.0. The regression method was used in this study due to the smaller sample size [16]. The outcome variables in the analysis were frequency-weighed accelerations ($a_{wx}$, $a_{wy}$, $a_{wz}$, and $a_{ws}$) and vibration dose values ($VDV_x$, $VDV_y$, $VDV_z$, and $VDV_s$). The predictor variables taken into consideration were personal characteristics of the drivers (age, BMI, and driving experience), vehicle-related factors (vehicle type, vehicle age, mileage, age of tyres, and seat pad thickness), speed of vehicle, and type of road. All variables were continuous except the type of vehicle and type of road, which were dummy variables. Dummy variables were re-coded as a one for truck and rough road, and zero for bus and smooth road. Two types of regression analysis methods were used in this study. In the first step,
univariate analysis was performed to determine the association of each outcome variable with predictor variables. In the second step, multiple regression analyses were carried out to find the independent variables which predict the level of vibration exposure as measured by outcome variables.

### Table 1. Descriptive statistics of study variables.

|                          | Mean±SD or % | Median | Skewness | Range | < HGCZ lower limit* (%) | Within HGCZ limits* (%) | > HGCZ upper limit* (%) |
|--------------------------|--------------|--------|----------|-------|-------------------------|-------------------------|-------------------------|
| **RMS acceleration**     |              |        |          |       |                         |                         |                         |
| \(a_{xx}\), m/s²        | 0.245±0.1    | 0.21   | 0.622    | 0.118-0.44 | 100                      | 0                       | 0                       |
| \(a_{yy}\), m/s²        | 0.238±0.121  | 0.187  | 1.354    | 0.13-0.324 | 90                       | 10                      | 0                       |
| \(a_{zz}\), m/s²        | 0.427±0.297  | 0.341  | 0.902    | 0.073-1.076 | 65                       | 25                      | 10                      |
| \(a_{xyz}\) (vector sum), m/s² | 0.663±0.33  | 0.479  | 1.238    | 0.339-1.441 | 30                       | 45                      | 25                      |
| A(8)\(_x\), m/s²        | 0.676±0.333  | 0.548  | 0.873    | 0.268-1.333 | 40                       | 35                      | 25                      |
| A(8)\(_y\), m/s²        | 0.435±0.301  | 0.332  | 0.675    | 0.08-0.99    | 65                       | 25                      | 10                      |
| **VDV exposure**         |              |        |          |       |                         |                         |                         |
| VDV\(_x\), m/s²\(^{1/3}\) | 2.949±1.451  | 2.765  | 0.561    | 1.307-5.643 | 100                      | 0                       | 0                       |
| VDV\(_y\), m/s²\(^{1/3}\) | 3.048±1.399  | 2.659  | 0.798    | 1.307-5.765 | 100                      | 0                       | 0                       |
| VDV\(_z\), m/s²\(^{1/3}\) | 4.915±2.616  | 4.699  | 0.035    | 1.063-8.765 | 90                       | 10                      | 0                       |
| VDV\(_{xyz}\) (vector sum), m/s²\(^{1/3}\) | 6.275±2.583 | 5.761  | 0.324    | 2.613-10.616 | 75                       | 25                      | 0                       |
| VDV(8)\(_x\), m/s²\(^{1/3}\) | 12.366±5.064 | 11.002 | 0.524    | 5.217-23.089 | 20                       | 55                      | 25                      |
| VDV(8)\(_y\), m/s²\(^{1/3}\) | 9.733±5.162  | 8.807  | 0.092    | 1.916-19.064 | 45                       | 50                      | 5                       |
| **Crest factor**         |              |        |          |       |                         |                         |                         |
| CF\(_x\)                 | 9.352±2.768  | 9.25   | -0.194   | 3.8-14.12    |                          |                         |                         |
| CF\(_y\)                 | 8.47±1.727   | 8.18   | 0.603    | 5.76-12.22   |                          |                         |                         |
| CF\(_z\)                 | 9.60±2.421   | 9.64   | 0.498    | 5.74-15.74   |                          |                         |                         |
| **Driver's personal characteristics** |          |        |          |       |                         |                         |                         |
| Age, years               | 37.8±10.2    | 42     | -0.108   | 23-52        |                          |                         |                         |
| BMI, kg/m²               | 24.8±2.8     | 24.5   | 0.153    | 19.9-29.2    |                          |                         |                         |
| Driving experience, years | 14.8±9.8    | 16.5   | 0.101    | 2-31         |                          |                         |                         |
| **Vehicle and road-related factors** |          |        |          |       |                         |                         |                         |
| Bus                      | 50%          |        |          |       |                         |                         |                         |
| Truck                    | 50%          |        |          |       |                         |                         |                         |
| Age of vehicle, years    | 7.1±1.6      | 7.4    | -0.729   | 3.8-9.4      |                          |                         |                         |
| Mileage, km              | 104078±26706 | 108210 | -0.649   | 54378-136548 |                          |                         |                         |
| Age of tyres, years      | 3±1.3        | 3.3    | -0.715   | 0.4-4.5      |                          |                         |                         |
| Speed of vehicle, km/hr  | 46.2±11.6    | 50     | -0.933   | 20-60        |                          |                         |                         |
| Seat pad thickness, cm   | 9.5±0.3      | 9.5    | 0.511    | 9.1-10       |                          |                         |                         |
| Type of road Smooth      | 45%          |        |          |       |                         |                         |                         |
| Rough                    | 55%          |        |          |       |                         |                         |                         |

SD, Standard deviation, RMS, Root mean square, A(8), 8-hours RMS acceleration, VDV, Vibration dose value, VDV(8), 8-hours Vibration dose value, BMI, Body mass index, km/hr, kilometer per hour.

*International Organisation for Standardisation (ISO) 2631-1 Health guidance caution for RMS acceleration: lower limit = 0.45 m/s², upper limit = 0.9 m/s²; for VDV: lower limit = 8.5 m/s¹/₃, upper limit = 17 m/s¹/₃.

In multiple regression analyses, independent variables were entered by using the simultaneous entry method and the stepwise entry method.
Table 2. Association between frequency-weighted RMS accelerations and various predictors of WBV by univariate analyses using simple linear regression models.

|                              | Frequency-weighted root mean square accelerations, m/s² | \( \beta \) (SE) | P   | \( \beta \) (SE) | P   | \( \beta \) (SE) | P   | \( \beta \) (SE) | P   |
|------------------------------|--------------------------------------------------------|-------------------|-----|-------------------|-----|-------------------|-----|-------------------|-----|
| Driver’s personal characteristics |                                                        |                   |     |                   |     |                   |     |                   |     |
| Age, years                   |                                                        | 0.664 (0.002)     | 0.001* | 0.637 (0.002) | 0.001* | 0.003* | 0.001* | 0.569 (0.006) | 0.009* | 0.687 (0.006) | 0.001* |
| BMI, kg/m²                   |                                                        | 0.464 (0.008)     | 0.039* | 0.357 (0.01)     | 0.123 | 0.336 (0.024) | 0.147 | 0.409 (0.026) | 0.073 |
| Driving experience, years    |                                                        | 0.641 (0.002)     | 0.001* | 0.682 (0.002) | 0.001* | 0.001* | 0.001* | 0.579 (0.006) | 0.007* | 0.698 (0.006) | 0.001* |
| Vehicle and road-related factors |                                                        |                   |     |                   |     |                   |     |                   |     |
| Type of vehicle (Truck vs. bus) |                                                        | -0.074 (0.048)   | 0.756 | -0.229 (0.054) | 0.331 | 0.067 (0.136) | 0.779 | -0.052 (0.151) | 0.828 |
| Age of vehicle, years        |                                                        | 0.542 (0.013)     | 0.013* | 0.322 (0.017) | 0.166 | 0.306 (0.042) | 0.19  | 0.416 (0.044) | 0.068 |
| Mileage, km                  |                                                        | 0.477 (0.000)     | 0.033* | 0.247 (0.000) | 0.293 | 0.28 (0.000) | 0.232 | 0.363 (0.000) | 0.116 |
| Age of tyres, years          |                                                        | 0.125 (0.019)     | 0.599 | 0.157 (0.022) | 0.507 | 0.238 (0.053) | 0.311 | 0.2 (0.059) | 0.397 |
| Speed of vehicle, km/hr      |                                                        | 0.689 (0.002)     | 0.001* | 0.597 (0.002) | 0.005* | 0.659 (0.005) | 0.002* | 0.721 (0.005) | <0.001* |
| Seat pad thickness, cm       |                                                        | -0.249 (0.085)    | 0.29  | -0.111 (0.099)  | 0.642 | -0.32 (0.233) | 0.169 | -0.281 (0.263) | 0.23  |
| Type of road (Rough vs. smooth) |                                                        | 0.656 (0.037)     | 0.002* | 0.528 (0.047) | 0.017* | 0.627 (0.107) | 0.003* | 0.676 (0.112) | 0.001* |

\( \beta \), Regression coefficient; SE, Standard error; BMI, Body mass index; km/hr, kilometer per hour.

* Dummy variables representing "Type of vehicle," "Type of road."

* Bold entries significant at \( p < 0.05 \) level.

3. Results

3.1. Descriptive Statistics of WBV Data

Table 1 presents the descriptive statistics of vibration data. The value of RMS acceleration was much higher along the vertical \( z \)-axis (mean = \( 0.427 \) range \( 0.073-1.067 \) m/s\(^2\)) than along the longitudinal \( x \)-axis (mean = \( 0.245 \), range \( 0.118-0.44 \) m/s\(^2\)) and the lateral \( y \)-axis (mean = \( 0.238 \), range \( 0.130-0.524 \) m/s\(^2\)). The mean of vector sum acceleration \( a_{VSD} \) was \( 0.663 \) m/s\(^2\) (range \( 0.339-1.441 \) m/s\(^2\)). The crest factor (CF) was also highest in the vertical direction (mean = \( 9.602 \), range \( 5.74-15.74 \)). Many drivers were having values of CF greater than 9 in all three directions. The magnitude of vibration dose value (VDV) was much higher in the \( z \)-direction (mean = \( 4.915 \) m/s\(^{1.75} \), range \( 1.063-8.765 \)) than in the longitudinal \( x \)-direction (mean = \( 2.949 \), range \( 1.307-5.643 \) m/s\(^{1.75} \)) and lateral \( y \)-direction (mean = \( 3.048 \), range \( 1.507-5.765 \) m/s\(^{1.75} \)). The mean of vector sum VDV\(_h\) was \( 6.275 \) m/s\(^{1.75} \) (range \( 2.613-10.616 \) m/s\(^{1.75} \)). Based on ISO 2631-1 standard it was found that 25% of drivers were exposed to WBV levels above the upper limit (0.9 m/s\(^2 \)) of Health guidance caution zone (HGCZ) for 8-hours equivalent RMS acceleration A(8) and 25% above the upper limit (17 m/s\(^{1.75} \)) of HGCZ for 8-hours equivalent VDV(8).

3.2. Univariate Regression Analysis

Tables 2 and 3 display the results of univariate analysis Tables 2 and 3. In Table 2, we see that the acceleration in the dominant \( z \)-axis, \( a_{VSD} \) was strongly associated (level of significance, \( p < 0.01 \)) with
driver’s age ($\beta = 0.569$), driving experience ($\beta = 0.579$), speed of vehicle ($\beta = 0.659$), and roughness of road ($\beta = 0.627$). The acceleration $a_{x,y}$ was associated with driver’s age ($\beta = 0.637$), driving experience ($\beta = 0.597$) and roughness of road ($\beta = 0.687$). The VDV $z$ was associated with driver’s age ($\beta = 0.689$), BMI ($\beta = 0.459$), driving experience ($\beta = 0.594$), speed of vehicle ($\beta = 0.714$) and roughness of road ($\beta = 0.726$).

Table 3 shows that vibration dose value in dominant z-axis, VDV $z$ was associated with driver’s age ($\beta = 0.593$), BMI ($\beta = 0.459$), driving experience ($\beta = 0.594$), speed of vehicle ($\beta = 0.714$) and roughness of road ($\beta = 0.726$). The VDV $y$ was associated with driver’s age ($\beta = 0.689$), BMI ($\beta = 0.455$), driving experience ($\beta = 0.735$), speed of vehicle ($\beta = 0.714$) and roughness of road ($\beta = 0.671$). The VDV $x$ was associated with driver’s age ($\beta = 0.593$), BMI ($\beta = 0.528$), driving experience ($\beta = 0.584$), age of vehicle ($\beta = 0.495$), mileage ($\beta = 0.444$), speed of vehicle ($\beta = 0.757$) and roughness of road ($\beta = 0.727$). The vector sum VDV $w$ was associated with driver’s age (0.748), BMI (0.54), driving experience (0.747), age of vehicle (0.457), speed of vehicle (0.852), and roughness of road (0.841).

This analysis shows that the predictors, like driver’s age, BMI, driving experience, speed of vehicle, and roughness of road had strong associations with frequency-weighted acceleration and vibration dose value in the vertical z-axis. Similar kinds of results were observed in the case of vector sum RMS acceleration and VDV.

| Frequency-weighted vibration dose value, m/s$^2$ | VDV $x$ | VDV $y$ | VDV $z$ | $\beta$ (SE) | $P$ | $\beta$ (SE) | $P$ | $\beta$ (SE) | $P$ |
|------------------------------------------------|---------|---------|---------|---------------|-----|---------------|-----|---------------|-----|
| Driver’s personal characteristics              |         |         |         |               |     |               |     |               |     |
| Age, years                                      | 0.593 (0.027) | 0.006 $^{*}$ | 0.689 (0.024) | 0.001 $^{*}$ | 0.593 (0.049) | 0.006 $^{*}$ | 0.748 (0.04) | <0.001 $^{*}$ |
| BMI, kg/m$^2$                                   | 0.528 (0.528) | 0.017 $^{*}$ | 0.455 (0.106) | 0.044 $^{*}$ | 0.459 (0.197) | 0.042 $^{*}$ | 0.54 (0.185) | 0.014 $^{*}$ |
| Driving experience, years                       | 0.584 (0.026) | 0.007 $^{*}$ | 0.735 (0.023) | <0.001 $^{*}$ | 0.594 (0.05) | 0.006 $^{*}$ | 0.747 (0.041) | <0.001 $^{*}$ |
| Vehicle and road-related factors                |         |         |         |               |     |               |     |               |     |
| Type of vehicle (Truck vs. bus)                 | -0.046 (0.666) | 0.848 $^{*}$ | -0.103 (0.639) | 0.665 (1.162) | 0.256 (1.183) | 0.276 (0.183) | 0.081 (0.734) | 0.734 |
| Age of vehicle, years                           | 0.495 (0.186) | 0.026 $^{*}$ | 0.337 (0.195) | 0.146 (0.372) | 0.269 (0.339) | 0.251 (0.039) | 0.457 (0.043) | 0.043 $^{*}$ |
| Mileage, km                                     | 0.444 (0.000) | 0.05 $^{*}$ | 0.263 (0.000) | 0.263 (0.000) | 0.262 (0.000) | 0.265 (0.000) | 0.414 (0.07) | 0.07 |
| Age of tyres, years                             | 0.015 (0.025) | 0.95 $^{*}$ | 0.066 (0.255) | 0.783 (0.465) | 0.234 (0.469) | 0.322 (0.469) | 0.118 (0.622) | 0.622 |
| Speed of vehicle, km/hr                         | 0.757 (0.019) | <0.001 $^{*}$ | 0.714 (0.020) | <0.001 $^{*}$ | 0.714 (0.037) | <0.001 $^{*}$ | 0.852 (0.028) | <0.001 $^{*}$ |
| Seat pad thickness, cm                          | -0.275 (1.158) | 0.241 $^{*}$ | -0.188 (1.140) | 0.429 (2.128) | -0.199 (2.051) | 0.4 (2.051) | -0.291 (0.214) | 0.214 |
| Type of road (Rough vs. smooth)                 | 0.727 (0.46) | 0.000 | 0.671 (0.479) | 0.001 $^{*}$ | 0.726 (0.831) | <0.001 $^{*}$ | 0.841 (0.644) | <0.001 $^{*}$ |

$\beta$, Regression coefficient; SE, Standard error; BMI, Body mass index; km/hr, kilometer per hour.
*Bold entries significant at $p < 0.05$ level.
Table 4. Association between frequency-weighted RMS accelerations and various predictors of WBV by multivariate analyses using multiple linear regression models.

| Driver’s personal characteristics | $a_{xz}$ (SE) | $P$ | $a_{yz}$ (SE) | $P$ | $a_{xz}$ (SE) | $P$ | $a_{yz}$ (SE) | $P$ |
|-----------------------------------|--------------|-----|---------------|-----|---------------|-----|---------------|-----|
| Age, years                        | 0.463        | 0.734 | -0.946        | 0.465 | 0.55          | 0.702 | 0.181         | 0.89 |
|                                   | (0.014)      |       | (0.015)       |       | (0.041)       |       | (0.041)       |       |
| BMI, kg/m$^2$                     | 0.104        | 0.739 | 0.283         | 0.344 | 0.142         | 0.666 | 0.173         | 0.565|
|                                   | (0.012)      |       | (0.012)       |       | (0.034)       |       | (0.034)       |       |
| Driving experience, years         | -0.063       | 0.961 | 1.778         | 0.165 | -0.083        | 0.951 | 0.446         | 0.72 |
|                                   | (0.013)      |       | (0.014)       |       | (0.04)        |       | (0.04)        |       |
| Vehicle and road-related factors  |              |      |               |      |               |      |               |      |
| Type of vehicle$^a$ (Truck vs. bus) | -0.038    | 0.89  | -0.071        | 0.78  | 0.087         | 0.762 | 0.012         | 0.963|
|                                   | (0.055)      |       | (0.058)       |       | (0.161)       |       | (0.163)       |       |
| Age of vehicle, years             | 0.598        | 0.638 | 0.325         | 0.784 | -0.644        | 0.631 | -0.125        | 0.918|
|                                   | (0.081)      |       | (0.087)       |       | (0.241)       |       | (0.244)       |       |
| Mileage, km                       | -0.185       | 0.875 | -0.281        | 0.799 | 0.093         | 0.94  | -0.035        | 0.975|
|                                   | (0.000)      |       | (0.000)       |       | (0.000)       |       | (0.000)       |       |
| Age of tyres, years               | 0.106        | 0.683 | 0.048         | 0.843 | 0.242         | 0.385 | 0.162         | 0.518|
|                                   | (0.021)      |       | (0.022)       |       | (0.061)       |       | (0.062)       |       |
| Speed of vehicle, km/hr           | 0.218        | 0.707 | 0.762         | 0.181 | 0.623         | 0.32  | 0.609         | 0.287|
|                                   | (0.005)      |       | (0.005)       |       | (0.015)       |       | (0.015)       |       |
| Seat pad thickness, cm            | 0.177        | 0.611 | 0.929         | 0.629 | -0.544        | 0.158 | -0.201        | 0.548|
|                                   | (0.125)      |       | (0.133)       |       | (0.37)        |       | (0.374)       |       |
| Type of road$^b$ (Rough vs. smooth) | 0.004    | 0.995 | 0.157 (0.141)| 0.153 | -0.239        | 0.729 | -0.397        | 0.531|
|                                   | (0.132)      |       | (0.389)       |       | (0.394)       |       |                |       |
| $R^2$                             | 0.676        | 0.715 | 0.64          | 0.64  | 0.701         | 0.701 |                |       |

$\beta_a$, Adjusted regression coefficient; SE, Standard error; BMI, Body mass index; km/hr, kilometer per hour; $R^2$, explained variance. Dummy variables representing "Type of vehicle," "Type of road."

Bold entries significant at $p < 0.05$ level.

3.3. Multivariate Regression Analysis

The results of multiple regression analyses have been presented in Tables 4, 5, and 6. Table 4 and Table 5 display results by simultaneous entry method. Results obtained by using the stepwise method have been shown in Table 6. Table 4 shows that $a_{xz}$, $a_{y}$, $a_{z}$, and $a_{yz}$ were not associated with any factor when the simultaneous entry method was used. The association between $a_{x}$ and speed of vehicle becomes significant ($\beta_a = 0.659$, Standard Error SE = 0.005, $p = 0.002$) when using the stepwise entry method (Table 6). The association between $a_{yz}$ and driving experience becomes significant ($\beta_a = 0.682$, SE = 0.002, $p = 0.001$) by stepwise entry method ($p < 0.05$). The associations between $a_{x}$ and driver’s age ($\beta_a = 0.405$, SE = 0.002, $p = 0.046$) and speed of vehicle ($\beta_a = 0.463$, SE = 0.002, $p = 0.025$) became significant after adopting stepwise method ($p < 0.05$). The associations between $a_{x}$ and driving experience ($\beta_a = 0.428$, SE = 0.006, $p = 0.025$) and speed of vehicle ($\beta_a = 0.481$, SE = 0.005, $p = 0.013$) became significant by stepwise entry method. These regression models explained 67.6% of variance for the x-axis, 71.5% for y-axis, 64% for z-axis, and 70.1% for vector sum RMS acceleration.

Table 5 reveals that only VDV$_s$ was related to speed of vehicle ($\beta_a = 1.037$, $p = 0.039$) when the simultaneous entry method was used. The association between driving experience and VDV$_s$ was close to significance ($p = 0.054$) by this method. The association between speed of vehicle and VDV$_s$ was also close to significance ($p = 0.08$) by the same method. The association between VDV$_s$ and type of road becomes significant ($\beta_a = 0.726$, SE = 0.831, $p = 0.000$) upon using stepwise entry method.
The results of multivariate regression models. The associations between VDV, speed of vehicle, age, and driver’s experience are vulnerable to high risks due to higher levels of dominance of vertical vibration. The study indicates that bus and truck drivers in India were experiencing medium to high levels of vibration and shock exposures. Magnitudes of vibration levels were higher in the vertical direction in comparison to vibration levels in the longitudinal and lateral directions. The results of multivariate analysis showed that the vibration exposure in the vertical direction was directly related to the speed of vehicle. A significant association was also found between shock exposure in the dominant z-axis and road roughness. High WBV exposure in the dominant Some of the earlier studies also support the dominance of vertical z-axis [1, 15]. The study shows that some vehicle drivers are vulnerable to high risks due to higher levels of vibration and shock exposures. In fact, 25% of drivers were exposed to

Table 5. Association between frequency-weighted vibration dose values and various predictors of WBV by multivariate analyses using multiple linear regression models.

| Predictor                          | VDV_x | VDV_y | VDV_z | VDV_s |
|-----------------------------------|-------|-------|-------|-------|
| **Driver’s personal characteristics** |       |       |       |       |
| Age, years                        | -0.53 | 0.693 | -1.518| 0.168 |
|                                   | (0.185)|       | (0.139)|       |
| BMI, kg/m^2                       | 0.141 | 0.647 | 0.224 | 0.117 |
|                                   | (0.155)|       | (0.255)|       |
| Driving experience, years         | 0.548 | 0.667 | 2.122 | 0.136 |
|                                   | (0.182)|       | (0.299)|       |
| **Vehicle and road-related factors** |       |       |       |       |
| Type of vehicle (Truck vs. bus)   | 0.009 | 0.972 | 0.117 | 0.552 |
|                                   | (0.735)|       | (1.21)|       |
| Age of vehicle, years             | 0.419 | 0.736 | 0.526 | 0.824 |
|                                   | (1.098)|       | (1.806)|       |
| Mileage, km                       | 0.149 | 0.897 | -0.61 | 0.503 |
|                                   | (0.000)|       | (0.000)|       |
| Age of tyres, years               | -0.13 | 0.611 | -0.128| 0.521 |
|                                   | (0.278)|       | (0.251)|       |
| Speed of vehicle, km/hr           | 0.44  | 0.446 | 1.037 | 0.052 |
|                                   | (0.069)|       | (1.14)|       |
| Seat pad thickness, cm            | 0.049 | 0.885 | 0.01  | 1.265 |
|                                   | (1.684)|       | (2.77)|       |
| Type of road (Rough vs. smooth)    | 0.204 | 0.751 | -0.807| 0.131 |
|                                   | (1.773)|       | (2.917)|       |
| **R^2**                           | 0.687 | 0.81  | 0.74  | 0.88  |

\( \beta \), Adjusted regression coefficient; SE, Standard error; BMI, Body mass index; \( \text{km/hr} \), kilometer per hour; \( R^2 \), explained variance. Dummy variables representing "Type of vehicle," "Type of road.

\(^{a}\) Bold entries significant at \( p < 0.05 \).

\(^{b}\) Bold entries close to the level of significance.

remaining only significant predictors (\( p < 0.05 \). The associations between VDV \( y \) and driving experience (\( \beta_y = 0.488, SE = 0.024, p = 0.010 \)), and speed of vehicle (\( \beta_y = 0.44, SE = 0.020, p = 0.018 \)) became significant when stepwise method is used (\( p < 0.05 \)). The association between VDV \( x \) and speed of vehicle becomes significant (\( \beta_x = 0.757, SE = 0.019, p<0.001 \)) by stepwise entry method \( (p < 0.05) \). The association between vector sum VDV and driver’s age becomes significant (\( \beta_z = 0.394, SE = 0.03, p = 0.004 \)) when using stepwise entry method (Table 6). These regression models explained 68.7% of variance for \( \text{VDV}_x \), 81% for \( \text{VDV}_y \), 74% for \( \text{VDV}_z \), and 88% for \( \text{VDV}_s \).

4. Discussion

4.1. Health Risk Due to WBV Exposure

The study indicates that bus and truck drivers in India were experiencing medium to high levels of vibration and shock exposures. Magnitudes of vibration levels were higher in the vertical direction in comparison to vibration levels in the longitudinal and lateral directions. The results of multivariate analysis showed that the vibration exposure in the vertical direction was directly related to the speed of vehicle. A significant association was also found between shock exposure in the dominant z-axis and road roughness. High WBV exposure in the dominant Some of the earlier studies also support the dominance of vertical z-axis [1, 15]. The study shows that some vehicle drivers are vulnerable to high risks due to higher levels of vibration and shock exposures. In fact, 25% of drivers were exposed to
WBV levels above the HGCZ when considering vector sum $A(8)$ and $VDV(8)$. The 8-hours RMS acceleration magnitude reached 1.333 m/s$^2$, with a mean value of 0.676 m/s$^2$, which was quite close to the HGCZ limits. The 8-hours $VDV$ magnitude reached 23.089 m/s$^{1.75}$, with an average magnitude of 12.366 m/s$^{1.75}$. The average crest factor value of vehicle drivers in the $z$-axis was more than 9, which points towards the presence of shock content in WBV exposure. This may be due to the roughness of road and the presence of speed breakers on the road.

4.2. Association Between Driver’s Personal Characteristics and WBV Exposure

The univariate and multivariate analyses show that the driver’s age and driving experience predict vibration exposure. Older and experienced drivers are exposed to higher WBV levels and intensive shocks. The effect of age on WBV exposure in vehicle drivers has also been confirmed in some previous studies [17]. These vibrations may thus be more harmful to older drivers, especially when their magnitude is more than ISO 2631-1 limit values. Univariate analyses showed a positive association between body mass index and $VDV$. We may hypothesize that obese drivers are more vulnerable to shock loads. A study by [18] on European drivers also confirms an increased risk for heavier persons with a high BMI.

4.3. Association Between Vehicle/Road-Related Factors and WBV Exposure

The univariate analysis shows that both age and mileage of the vehicles are significantly associated with WBV exposure only in $x$-direction. No such association has been found in multivariate analysis. Non-significant associations of vehicle age and mileage in $y$- and $z$-directions indicate that WBV levels are not affected by vehicle age or mileage in these directions. The vehicle age may have its effect on WBV exposure levels due to improved technology and wear & tear of moving parts. Older buses [19] and old model trucks [20] are associated with higher levels of WBV exposure. Both univariate and multivariate analyses show the association of speed with WBV exposure. Previous studies conducted on subway train operators and truck drivers also show that higher speed results in greater levels of WBV [16, 20]. Similar results were found in a study on forklift drivers [17]. The univariate analysis shows that rougher roads are related to higher levels of vibration magnitudes in all the orthogonal axes and the vector sum of the axes. On a rough road, vibrations are influenced by increased jostling because of potholes and irregularities of the road surface. On the contrary, vibrations on smooth roads are affected more by the engine, tyres, suspension, and pebbling of the road surface[22]. Rough road conditions resulted in greater WBV exposures in vehicle drivers [23]. This study shows that type of vehicle (bus or truck) is not a predictor of WBV exposure. It means exposure levels in both types of vehicles are not very different. Similarly, age of tyres or seat pad thickness is not significantly associated with the levels of WBV exposure. This is in line with previous studies [8, 24] that demonstrated that seats had a limited role in attenuating the WBV exposure.

### Table 6. Results of multiple regression analyses by stepwise entry method.

|                        | $a_{xx}$ | $a_{yy}$ | $a_{zz}$ | $V_{Dx}$ | $V_{Dy}$ | $V_{Dz}$ | $V_{Ds}$ |
|------------------------|----------|----------|----------|----------|----------|----------|----------|
| Driver’s age           | $\beta_a$ | 0.405    |          |          |          |          |          |
|                        | $p$      | 0.046    |          |          |          |          |          |
| Driving experience     | $\beta_a$ |          |          | 0.428    | 0.025    | 0.488    |          |
|                        | $p$      |          |          | 0.001    |          | 0.01     |          |
| Speed of vehicle       | $\beta_a$ | 0.463    | 0.659    | 0.481    | < 0.001  | 0.44     |          |
|                        | $p$      | 0.025    | 0.002    | 0.013    |          |          |          |
| Type of road'          | $\beta_a$ |          |          |          |          |          | 0.726    |
|                        | $p$      |          |          |          |          |          | < 0.001  |

$\beta_a$, Adjusted regression coefficient; km/hr, kilometer per hour.

Dummy variables representing “Type of road.
Significant at $p < 0.05$ level.
5. Conclusions
This study was carried out following the guidelines of ISO-2631-1 and it was found that Indian bus and truck drivers are exposed to medium to high levels of vibration magnitudes. Following conclusions and recommendations may be summarised from the results of the study:

- Based on 8-hours vector sum acceleration, i.e., \((A(8)_s)\) and vibration dose value, i.e., \((VDV(8)_s)\), 25% of the drivers were exposed to high levels of WBV, above the ISO 2631-1 limit values.
- Based on 8-hours z-axis acceleration i.e., \((A(8)_z)\) and vibration dose value, i.e., \((VDV(8)_z)\), 10% of the drivers were exposed to high levels of WBV, above the ISO 2631-1 limit values.
- The WBV exposure magnitude of both frequency-weighted root mean square acceleration and vibration dose value were much higher along the z-axis than along the x-axis and y-axes.
- The crest factor CF which measures the shock component of the vibration ranged between 5.74 and 15.74. The value of crest factor above 9, indicates the use of fourth power averaging method (root-mean-quad) to assess possible adverse health effects.
- The whole-body vibration and shock exposures were related to the driver’s personal factors like age, BMI, and driving experience.
- The univariate and multiple linear regression showed that vibration magnitudes experienced by the drivers increased with vehicle speed. Self-imposed speed limits may help the drivers in reducing the levels of vibration magnitudes.
- The road roughness played a major role in increasing the level of vibration magnitude. This may be due to the presence of higher road irregularities on a rough road. There is a great need to improve the quality of roads in India as bad road conditions are responsible for the poor vibration health of drivers and passengers.
- The government and private authorities should take some concrete steps to make the drivers aware of human vibration exposure and its negative health effects.

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