Measurement and evaluation of whole body vibration of agricultural tractor operator

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Abstract: Exposure of whole body vibration (WBV) influences performance, comfort, and long term health risks of tractor operator. Therefore, measurement and evaluation of WBV parameters should be carried out to find probable effects on the health of tractor operators. In this study, a system was designed to measure the WBV of agricultural tractor operators and evaluated the hazard risks on operator's body according to the ISO standards, and implementation of the WBV test in the official testing station was also suggested. A tri-axial accelerometer was employed to measure vibrations transmitted to the seated operator body as a whole through the supporting surface of the buttock on four typical farm roads under different speeds. The vector sum $A(8)$ exposures on the rough tracks (earthen and grassland roads) exceeded the action limits of 0.5 m/s^2 at a 10.9 km/h forward speed and reached to the action limit value at a 16.0 km/h forward speed on the concrete road. The vector sum of $VDV(8)$ exposures did not exceed the action limits of 9.1 m/s$^{1.75}$ and was greater on the grassland road. The vector sum $S_{ed}(8)$ exposures values exceeded the moderate probability of an adverse health limit of 0.5 MPa on all farm roads at high forward speeds and exceeded the high probability of an adverse health limit of 0.8 MPa on asphalt, concrete, and grassland roads which should be lower than the exposure limit values as suggested by the ISO and EC standards. The WBV evaluation procedure should be considered for implementation at the official tractor test station, which would response to domestic and international tractor test regulations and improve the market competitiveness.

Keywords: agricultural tractor, whole body vibration, tractor operator, driving safety, ride comfort, test standard, health risk

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1 Introduction

Research trends for safety and comfort issues of agricultural tractor operators have been reviewed and test standards were compared for possible revisions or improvements. Among the safety and comfort issues, inclusion of visibility and whole body vibration of agricultural tractor operators have been emphasized for implementation at the official tractor test stations[1-3]. Agricultural tractors are extensively used for on/off-road transportation and for different field operations; however, it is widely recognized that tractor operators are exposed to high levels of whole-body vibration (WBV) during typical farm operations[4]. Continuous exposure of this whole-body vibration could result in biological, mechanical, physiological and psychological damages to tractor operators[5]. Vibration could also adversely

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affect operator's comfort and work performance[6]. Addressing the health risks posed by occupational exposure to WBV, the European Physical Agents (Vibration) in Directive 2002/44/EC specifies limits on daily occupational WBV exposure and mandates the application of ISO2631-1 as the metrological framework for measurements of daily WBV exposure severity and the application of the appropriate frequency weightings[7]. Therefore, it would be necessary to evaluate the effects of the exposure time and vibration dose on health during tractor operations and to maintain WBV exposures below the exposure limit level for reducing the probability of adverse health effects on the tractor operators.

Vibrations are reduced usually by vibration damping seat suspensions. Particularly for agricultural tractors, integrated solutions to reduce vibrations transmitted to the driver may include damping seat suspensions, front and rear axle suspensions, suspended cabs and shock absorbers[8-12]. Exposure to WBV occurs mostly in seated postures while driving. Moreover, WBV is usually transmitted through the human body when the human body is in contact with vibrating surfaces (i.e., a driving seat, a seat back-rest or floor in vehicles). In general, if the human body is continuously exposed to WBV, it is possible that human body will have adverse effects from the WBV[13]. In recent years, there has been an increased emphasis on the health and safety of agricultural tractor operators. Among the safety concerns, the operator's WBV is of primary importance for efficient and safe operation of tractors.

The test procedures for the measurement of WBV and human responses to the WBV exposures are evaluated by two main standards, ISO2631-1[14] and ISO2631-5[15]. ISO2631-1 defines methods for the measurement of periodic, random, and transient WBV in relation to human health and comfort, the probability of vibration perception, and the incidence of motion sickness. ISO2631-5 provides guidance on assessment of vibration containing multiple shocks and focuses on the lumbar response of humans exposed to WBV. ISO5008[16] specifies methods for measuring the WBV exposed to agricultural tractor operators on standard test tracks and non-standard test conditions. This standard has been set up to measure the WBV of an operator on a 100 m smoother track and a 35 m rougher track at specified forward speeds. These two tracks are used to limit the variability of some field parameters such as followed path, speed fluctuations, weather, temperature, soil conditions. Each test track consists of two parallel strips suitably spaced for wheel track of the tractor. The surface of each strip is either cast in smoothly surfaced concrete or formed of pieces of wood, steel, or concrete in a base framework. And each track strip is defined by the ordinates of elevation with respect to a level base. The elevation is defined at intervals of 80 mm (for the rougher) and 160 mm (for the smoother tracks) along each strip as shown in Figure 1[17]. Where the strips are constructed with pieces of wood, steel or concrete, these are 60-80 mm thick.

Figure 1 ISO100-m smooth track (left) and ISO35-m rough track

Some researchers conducted field tests to study WBV in agricultural tractors, and most evaluations of WBV exposures were measured and evaluated in terms of ISO2631-1 standard. There have been very few studies evaluated the WBV parameters according to the ISO2631-5 standard. ISO2631-1 only includes the means of weighting the vibration levels at different frequencies to assess the frequency sensitivity to WBV, while ISO2631-5 analyzes the effect of multiple shocks in relation to human health based on lumbar spine response. Moreover, evaluation of WBV has not been implemented in official testing standards for agricultural tractors in Korea. Regarding these issues, this study aimed to design and demonstrate the test procedures according to the ISO5008 standard for the WBV measurement of tractor operators which has not been approved by the official tractor test station in many countries including Korea. This study also evaluated the effects on the health of the tractor operators according to the ISO2631-1 and ISO2631-5 standards.

2 Materials and methods

2.1 WBV measurement system

A measurement system was designed for the whole body vibration measurement of agricultural tractor operators based on ISO 2631-1, ISO 2631-5 and ISO 5008 as vibration issue has not been approved by the official tractor test stations. Specifications of the tractor used for vibration measurement are given in the Table 1. Due to the absence of artificial standard test tracks, the WBV was measured under non-standard test conditions on typical Korean farm roads (Figure 2), and the data were acquired maintaining the field parameters as nearly constant as possible.

Table 1 Specifications of tractor used for WBV evaluation

Item	Specifications
Model	DK470 (Daedong Co., Ltd.)
Power/kW	35
Traction	MFWD
Size/mm	3430 (L) ×1920 (W) ×2434 (H)
Seat height/mm	500 (L) ×450 (W) ×600 (H)
Suspension system	Adjustable suspension seat (without axle or cab suspension)
Front tire pressure/kPa	205
Rear tire pressure/kPa	196

a. Asphalt road b. Concrete road

c. Grassland road d. Earthen road

Figure 2 Measurement of WBV under non-standard test conditions

A tri-axial accelerometer (model: 356A01, PCB Piezotronics, Inc., NY, USA) was employed to measure vibrations transmitted to the seated operator body as a whole through the supporting surface of buttock. The weight of tractor operator was 72 kg. The accelerometer had a frequency sensitivity range of 2-8000 Hz. A semi rigid disc was designed and fabricated (Figure 3) according to the instructions and dimensions given in ISO10326-1[18]. The disc was 12 mm in thickness and made of 85 Shore-A molded plastic. The accelerometer was mounted according to ISO5348[19].

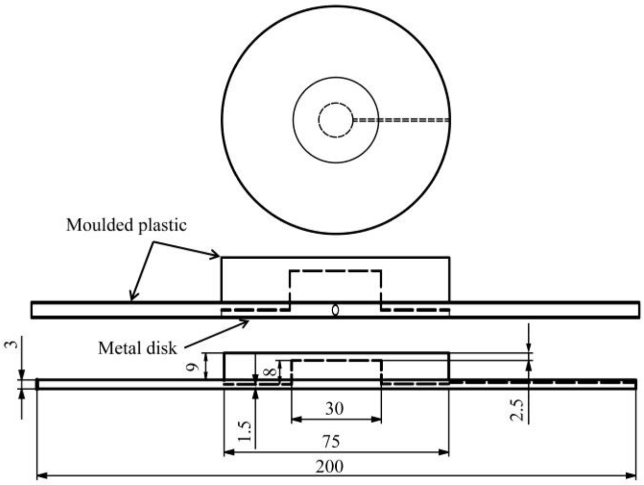

Figure 3 Design of semi-rigid disc for tri-axial whole body vibration seat accelerometer according to the dimensions of ISO 10326-1. All dimensions are in mm

An 8-channel data logger (model: NI cDAQ-9178; National Instruments, USA) and a 4-channel module (model: NI 9234, National Instruments, USA) were used to collect WBV exposures according to the ISO standards. A LabVIEW software program (version 2010; National instrument; Austin, Texas, USA) was applied to collect WBV exposures, and the data were analyzed using Matlab R2010a software package (ver. 7.10, The MathWorks, USA). Vibration measurement instrumentation and mounting of tri-axial accelerometer on the seat of tractor operator are shown in Figure 4.

Figure 4 WBV measurement instrumentation at operator's seat (left), accelerometers (middle), and data acquisition unit (right)

2.2 Procedures for the WBV evaluation

Standardized tests for measuring the WBV of the tractor operator are performed while the operator is exposed on standard rougher and smoother test tracks at a prescribed range of speeds in accordance with the methodology of ISO5008. For each pass, acceleration levels are measured simultaneously in three perpendicular directions (*X*-longitudinal, *Y*–transversal, and *Z*-vertical) upon the surface of the operator's seat. The measured values are then frequency-weighted by multiplying the horizontal (X and Y) axis measurements with a factor of 1.4 to make allowance for the sensitivity of human body to vibration in these directions, before derivation of root mean square (r.m.s.) acceleration values in accordance with the procedure of ISO2631-1. In this study, the WBV exposures were measured in non-standard test conditions on four different roads that tractors normally travel during on/off road transportation. Test track conditions and forward speeds during WBV measurement are shown in Table 2. Three replications were run for each of the travel speed. Considering the ISO standards, the procedures for the WBV evaluation were developed as illustrated in Figure 5.

Table 2 Test tracks and forward speeds used during vibration measurement

Test tracks	Forward speeds /km h^{-1}
35 m earthen road (rough tracks)	2.6, 3.8, 6.0, 7.7, 10.9
35 m grassland road (rough tracks)	2.6, 3.8, 6.0, 7.7, 10.9
100 m concrete road (smooth tracks)	3.8, 6.0, 7.7, 10.9, 16.0
100 m asphalt road (smooth tracks)	3.8, 6.0, 7.7, 10.9, 16.0

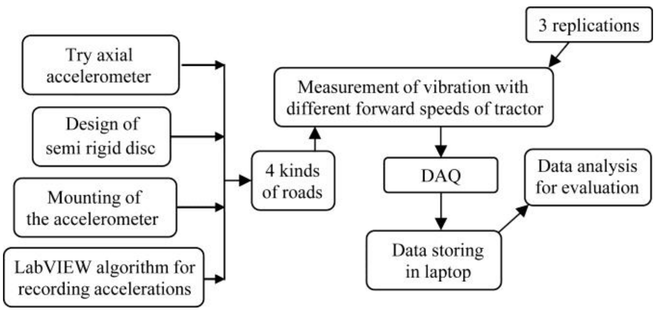

Figure 5 Procedures of evaluation of the operator's WBV

The algorithms for calculating the ISO2631-1 and ISO2631-5 WBV exposure parameters were performed using the LabVIEW program and calculated for each road type. According to ISO2631-1, WBV exposures included:

The weighted root mean square (r.m.s.) average weighted vibration (A_w) which was extrapolated to an 8-hour daily value (A (8)) (unit: m/s^2).

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

$$A_w(8)=A_w\left[\frac{28800}{\text{measurement time}}\right]^{1/2} \quad (1)$$

(i) The vibration dose value (VDV) which was extrapolated to an 8-hour daily value (VDV(8)) (unit: m/s$^{1.75}$).

$$VDV=\left[\frac{1}{T}\int_0^T a_w^4(t)dt\right]^{1/4},$$

$$VDV(8)=VDV\left[\frac{28800\text{ s}}{\text{measurement time, s}}\right]^{1/4} \quad (2)$$

(ii) According to ISO2631-5, the impulsive WBV exposures included the daily equivalent static compression dose S_{ed} which was derived from a vector sum of the D_k exposures (unit: MPa). D_k was the sixth power of amplitude of acceleration, and these values were also normalized to an 8-hour daily value $D_k(8)$ (unit: m/s^2). As a result of the normalization, all S_{ed} values were 8 h daily equivalents $S_{ed}(8)$. $D_k(8)$ and $S_{ed}(8)$ were calculated from biomechanical models of ISO2631-5.

$$D_k=\left[\sum_i a_{il}^6\right]^{1/6},\quad D_k(8)=D_k\left[\frac{28800\text{ s}}{\text{measurement time, s}}\right]^{1/6} \quad (3)$$

$$S_{ed}(8)=[((m_k D_k(8)6))]^{1/6} \quad (4)$$

where, $k=x$, y, or z; A_{ik} is the i^{th} peak of response acceleration $a_{ik}(t)$ and according to ISO2631-5 the recommended values for m_k are $m_x=0.015$ MPa/(m/s^2), $m_y=0.035$ MPa/(m/s^2), $m_z=0.032$ MPa/(m/s^2).

(iii) Health effects were evaluated based on the vector sum A(8), VDV (8), and S_{ed}(8) daily equivalent exposures.

$$A(8)_{all}=[(1.4A(8)_x)^2)+(1.4A(8)_y)^2)+(1.4A(8)_z)^2)]^{1/2} \quad (5)$$

$$VDV(8)_{all}=[(1.4VDV(8)_x)^4)+(1.4VDV(8)_y)^4)+(1.4VDV(8)_z)^4)]^{1/4} \quad (6)$$

$$S_{ed}(8)_{all}=[(0.015D_{kx}(8)_x)^6)+(0.035D_{ky}(8)_y)^6)+(0.032D_{kz}(8)_z)^6)]^{1/6} \quad (7)$$

3 Results and discussion

3.1 WBV exposures

The root mean square (r.m.s.) or A(8) produces a value which is an average vibration exposure adjusted to represent an 8-h working day, whereas the VDV represents cumulative exposure to vibration over the working day. The frequency-weighted seat acceleration levels found in different road surfaces are shown in Figure 6. The WBV emission levels were found to increase in proportion with forward speed in each road.

The rate of increase was found the highest on earthen road whereas lower exposures were found on asphalt road.

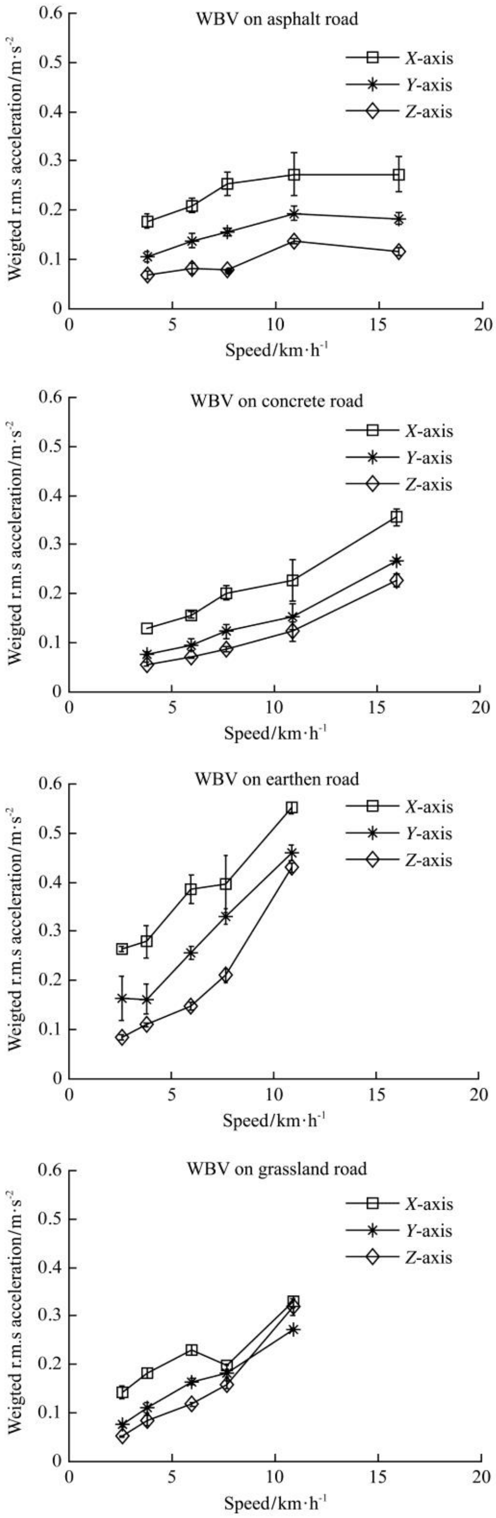

Figure 6 WBV measured with various roads with different speeds (1.4 multiplier)

From Figure 6, it was shown that the type of roads and forward speeds had significant effects on the extrapolated 8-hour daily weighted r.m.s. average weighted vibration value ($A(8)$). Weighted r.m.s values increased with the increase of speed, and this trend was found higher on the rough tracks (i.e., grassland roads and earthen roads). The highest acceleration emission was found in earthen roads, crossing daily action value of 0.5 m/s^2 on X-axis. Deboli et al.[20] reported r.m.s acceleration values on ISO track as 0.23-0.32 m/s^2 for X-axis with a speed range of 4-6 km/h, 0.15-0.5 m/s^2 for Y-axis with a speed range of 4-6 km/h, and 0.47-0.62 m/s^2 for Z-axis accelerations. In ISO track, the wooden slats distance and the height differences between the two strip tracks caused high horizontal acceleration at low forward speeds. In this study, r.m.s. average weighted accelerations were found as 0.17-0.27 m/s^2, 0.13-0.35 m/s^2, 0.14-0.33 m/s^2 and 0.26-0.55 m/s^2 for X-axis accelerations on asphalt, concrete, grassland, and earthen roads, respectively. In the case of Y-axis, r.m.s. average weighted accelerations were found as 0.11-0.19 m/s^2, 0.12-0.27 m/s^2, 0.10-0.27 m/s^2, and 0.16-0.46 m/s^2 on asphalt, concrete, grassland, and earthen roads, respectively. For Z-axis accelerations, it was found as 0.12-0.14 m/s^2, 0.10-0.13 m/s^2, 0.12-0.32 m/s^2, and 0.11-0.43 m/s^2 on asphalt, concrete, grassland, and earthen roads, respectively.

VDV found at each axis for each kind of road with respect to the speeds are shown as an example in Figure 7. It also can be found from the figure, and the type of roads and forward speeds had significant effects on the extrapolated 8-hour daily value VDV values. Vibration dose value was higher on weighted X-axis, whereas it was a bit higher for Z-axis on grassland road.

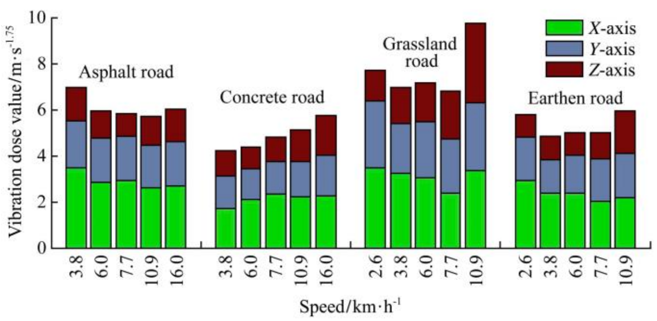

Figure 7 VDV found in various roads with respect to different speeds

3.2 WBV evaluation

Acceleration values were obtained at different speeds on four kinds of typical farm roads, and evaluations were done based on ISO12631-1 and ISO2631-5 standards.

The vector sums *A*(8) exposures measured on different roads are shown in Figure 8. On the rough tracks (earthen and grassland roads), the vector sum *A*(8) values exceeded the action limits of 0.5 m/s^2 at a 10.9 km/h forward speed. On the concrete road, it reached to the action limit value at a 16.0 km/h forward speed. Based on the health hazard assessment of ISO standards, if the tractor operator operates the agricultural tractor with these forward speeds for a long time, there is a probability of adverse health effect to the tractor operator.

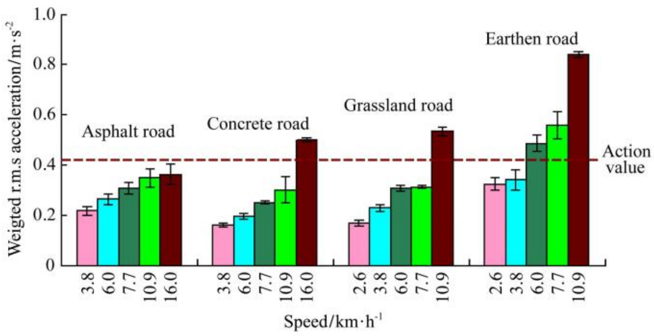

Figure 8 Vector sum A (8) exposures in each road with respect to forward speed

VDV values are opposed to r.m.s values and more sensitive to the amplitude peaks associated with shocks. According to ISO2631-1, the *VDV*(8) daily action limit value, and exposure limit value are 9.1 $m/s^{1.75}$ and 14.8 $m/s^{1.75}$, respectively. In our evaluation, the vector sum of *VDV*(8) exposures did not exceed the action limits of 9.1 $m/s^{1.75}$; however, it was greater on grassland road (Figure 9). The results showed that the *VDV*(8) values in smooth roads were well below the action limit due to absence of multiple shocks.

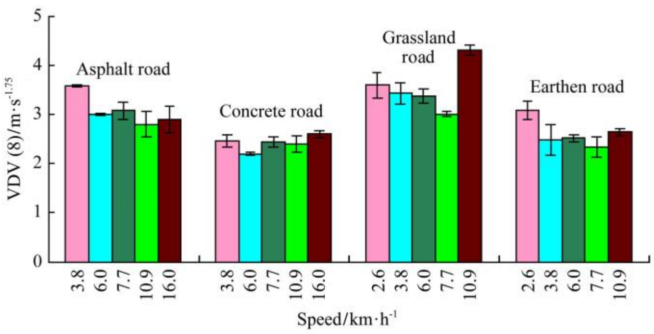

Figure 9 Vector sum VDV (8) exposures in each road with respect to forward speed

The vector sum S_{ed} (8) exposures measured on different roads are shown in Figure 10. According to the ISO 2631-5 standard, S_{ed} (8) values less than 0.5 MPa represents a low probability of adverse health effect, and 0.5-0.8 MPa represents a moderate probability. Above 0.8 MPa represents a high probability of adverse health effect. In our evaluation, the S_{ed} (8) values exceeded the moderate probability of adverse health limit of 0.5 MPa on all farm roads at moderate to high forward speeds. Moreover, it exceeded the high probability of an adverse health limit of 0.8 MPa on asphalt, concrete, and grassland roads at high forward speeds. These results showed the probability of adverse health risks on tractor operator in moderate and high speeds during farm operations on typical farm roads.

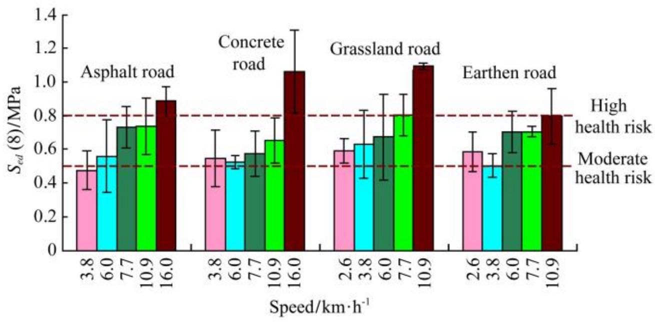

Figure 10 Vector sum S_{ed} (8) exposures in each road with respect to forward speed

The mixed model analysis showed that WBV exposures were significantly different based on the road types (Table 3). For each vibration exposure, standard ANOVA tests were conducted among the road conditions for the same forward speed. Different letters are flanked on the mean values on the same line, indicating that the same letters are not significantly different at 5% significance level. Significant differences were found for *A*(8) exposures among the road conditions with respect to forward speeds. Higher *A*(8) values were found with increase of forward speeds from 2.6 to 10.9 km/h speeds, and the highest values were found on earthen road followed by grassland road, asphalt road, and concrete road. For speed with 16 km/h, higher *A*(8) values were found as 0.5 m/s^2 on concrete road compared to asphalt road. Significant differences were also found for *VDV*(8) exposures among the road conditions with respect to forward speeds. Similar to *A*(8) exposures, *VDV*(8) values were found higher with the increase of forward speeds from 2.6 km/h to 10.9 km/h speeds, but higher values were found on grassland road followed by earthen road, asphalt road, and concrete road. Higher *VDV*(8) value was found as 2.89 $m/s^{1.75}$ on asphalt road compared to concrete road with 16 km/h forward speed. No significant differences were found for $S_{ed}(8)$ exposures among the road conditions with respect to forward speeds, and only the exception was observed on concrete road at 10.9 km/h speed. $S_{ed}(8)$ values were much higher than the high health risk value of 0.8 MPa at 16 km/h forward speed on each road, showing a high probability of an adverse health effects on tractor operator.

Table 3 Mean (S.D) of vibration parameters on different roads with respect to different speeds. Parameter means with different superscript letters are statistically and significantly different for each road condition

Exposure parameter	Speed /km h^{-1}	Road conditions			
		Asphalt road	Concrete road	Grassland road	Earthen road
$A(8)$ m/s^2	2.6	-	-	0.16^a (±0.01)	0.32^b (±0.02)
	3.8	0.22^a (±0.01)	0.16^b (±0.01)	0.23^a (±0.01)	0.34^c (±0.04)
	6.0	0.26^a (±0.02)	0.19^b (±0.01)	0.31^a(±0.01)	0.48^c (±0.03)
	7.7	0.31^a (±0.02)	0.25^a (±0.01)	0.31^a (±0.01)	0.56^b (±0.05)
	10.9	0.35^a (±0.03)	0.30^b (±0.05)	0.53^a (±0.01)	0.84^c (±0.01)
	16.0	0.36^a (±0.04)	0.50^b (±0.01)	-	-
VDV(8) ($m/s^{1.75}$)	2.6	-	-	3.59^a (±0.26)	3.07^b (±0.18)
	3.8	3.58^a (±0.18)	2.46^b (±0.12)	3.42^a (±0.21)	2.47^b (±0.31)
	6.0	2.99^a (±0.22)	2.19^b (±0.03)	3.36^a (±0.15)	2.51^b (±0.07)
	7.7	3.07^a (±0.16)	2.43^b (±0.11)	2.99^a (±0.05)	2.34^b (±0.21)
	10.9	2.79^a (±0.26)	2.39^b (±0.16)	4.29^c (±0.10)	2.63^{ac} (±0.07)
	16.0	2.89^a (±0.26)	2.59^a (±0.06)	-	-
$S_{ed}(8)$ (MPa)	2.6	-	-	0.59^a (±0.07)	0.58^a (±0.12)
	3.8	0.47^a (±0.11)	0.54^a (±0.16)	0.63^a (±0.20)	0.50^a (±0.06)
	6.0	0.55^a (±0.21)	0.52^a (±0.04)	0.67^a (±0.25)	0.70^a (±0.12)
	7.7	0.73^a (±0.12)	0.57^a (±0.13)	0.80^a (±0.12)	0.70^a (±0.03)
	10.9	0.73^a (±0.16)	0.65^b (±0.13)	1.09^a (±0.02)	0.79^a (±0.16)
	16.0	0.88^a (±0.08)	1.06^a (±0.25)	-	-

Note: *Axis: 1.4x, 1.4y, z.

4 Conclusions

A measurement system was designed, and the procedure was demonstrated for the whole body vibration (WBV) of tractor operator. A tri-axial accelerometer was employed to measure WBV emissions on operator's seat of tractor on four typical farm roads under different speeds, and the WBV exposures were evaluated in accordance with ISO5008, ISO2631-1 and ISO2631-5 standards. The vibration analysis showed that the WBV exposures were significantly different based on road types and forward speeds. On the smooth road, the WBV exposures in the operator's seat were significantly lower compared to rough roads, crossing the exposure limits which showed high probability of an adverse health effects on tractor operator. Implementation of the WBV procedure would aid tractor industry and response to domestic and international tractor test regulations.

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[References]

[1] Kabir M S, Ryu M J, Chung S O, Kim Y J, Choi C H, Hong S J, et al. Research trends for performance, safety, and comfort evaluation of agricultural tractors: A review. Journal of Biosystems Engineering, 2014; 39(1): 21–33.

[2] Kabir M S, Chung S O, Kim Y J, Hong S J. Comparison of Test standards for performance and safety of agricultural tractors: A review. Journal of Biosystems Engineering, 2014; 39(3): 158–165.

[3] Kabir M S, Song M Z, Chung S O, Kim Y J, Kim S C, Ha J K. Visibility evaluation for agricultural tractor operators according to ISO 5006 and 5721-1 standards. Journal of Biosystems Engineering, 2015; 40(1): 19–27.

[4] Scarlett A J, Price J S, Stayner R M. Whole-body vibration: Evaluation of emission and exposure levels arising from agricultural tractors. Journal of Terramechanics, 2007; 44: 65–73.

[5] Goering C E, StoneM L, Smith D W, Turnquist P K. Human factors and safety. Chapter 15 in Off-Road Vehicle Engineering Principles. 2003. ASAE, St. Joseph, MI. pp 421–462.

[6] Newell G S, Mansfield N J. Evaluation of reaction time performance and subjective workload during whole-body vibration exposure while seated in upright and twisted postures with and without armrests. International Journal of Industrial Ergonomics, 2008; 38: 499–508.

[7] Rimell A N, Mansfield N J. Design of digital filters for frequency weightings required for risk assessments of workers exposed to vibration. Industrial Health, 2007; 45: 512–9.

[8] Marsili A, Ragni L, Santoro G, Servadio P, Vassalini G. Innovative systems to reduce vibrations on agricultural tractors: comparative analysis of acceleration transmitted through the driving seat. Biosystems Engineering, 2002; 81(1): 35–47.

[9] Hansson P A. Working space requirement for an agricultural tractor axle suspension. Biosystems Engineering, 2002; 81(1): 51–57.

[10] Bouazara M, Richard M J, Rakheja S. Safety and comfort analysis of a 3-D vehicle model with optimal non-linear active seat suspension. Journal of Terramechanics, 2006; 43: 97–118.

[11] Deprez K, Moshou D, Ramon H. Comfort improvement of a non-linear suspension using global optimization and in situ measurements. Journal of Sound and Vibration, 2005; 284: 1003–1014.

[12] Deprez K, Moshou D, Anthonis J, Baerdemaeker J D, Ramon H. Improvement of vibrational comfort by passive and semi-active cabin suspensions. Computers and Electronics in Agriculture, 2005; 49: 431–440.

[13] Park M S, Fukuda T, Kim T, Maeda S. Health risk evaluation of whole-body vibration by ISO 2631-5 and ISO 2631-1 for operators of agricultural tractors and recreational vehicles. Industrial Health, 2013; 51: 364–370.

[14] ISO 2631-1: 1997. Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1: General requirements. Geneva, Switzerland: ISO.

[15] ISO 2631-5:2004. Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 5: Methods for evaluation of vibration containing multiple shocks. Geneva, Switzerland: ISO.

[16] ISO 5008: 2002. Agricultural wheeled tractors and field machinery - Measurement of whole-body vibration of the operator. Geneva, Switzerland: ISO.

[17] Scarlett A J, Price J S, Stayner R M. Whole-body vibration: Initial evaluation of emissions originating from modern agricultural tractors. Health and Safety Executive (HSE) Contract Research Report No. 413/2002 – HSE Books, ISBN 0717622762, 2002.

[18] ISO 10326-1: 1992. Mechanical vibration - Laboratory method for evaluating vehicle seat vibration. Geneva, Switzerland: ISO.

[19] ISO 5348: 1982. Mechanical vibration and shock - Mechanical mounting of accelerometers. Geneva, Switzerland: ISO.

[20] Deboli R, Calvo A, Preti C. Comparison between ISO 5008 and field WBV tractor values. Journal of Agricultural Engineering, 2012; 43(2): 49–54.