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Tractor Vibration Severity and Driver Health: a Study from Rural India

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Measurements of vibrations were conducted on tractors of different sizes under varying terrain conditions. Analysis has been done in terms of root mean square (rms) accelerations in one-third-octave band and International Standard Organisation (ISO) weighted overall rms. The values were compared with ISO 2631-1,1985 and 1997 standards. The comparisons reveal that measured vibrations exceed the '8 h exposure limit' in one-third-octave frequency band procedure of ISO 2631-1 (1985) on both farm and non-farm terrains. In the overall ISO-weighted rms acceleration procedure of ISO 2631-1 (1997) in all farm and non-farm terrains working time of 3 h exceeded the upper limit of 'health guidance caution zone'. A tractor-operator model was adapted for prediction of the rms accelerations on the ISO 5008 track. This model gave results for vibration exposure similar to measured values. Effect of whole-body vibrations on degenerative changes in the spine of 50 tractor-driving farmers was evaluated by comparing them with a control group of 50 non-tractor-driving farmers matched for age, sex, ethnic group, land holding and work routine. All participants were interviewed in detail for occurrence of low back pain, examined clinically and a magnetic resonance image (MRI) of the lumbar spine region was obtained. Evaluation of data revealed that the tractor-driving farmers complain of backache more often than non-tractor-driving farmers but there was no significant objective difference in clinical or magnetic resonance imaging between the two groups.

1. Introduction

Occupational health problems of agricultural workers have not received significant attention in low-income countries (LICs). This is particularly true for tractor drivers who operate the tractor in extreme temperatures, high level of suspended particles and without vibration-attenuating designs of tractors and tractor seats. Tractors in high-income countries (HICs) have become very sophisticated and almost all have enclosed environment-controlled suspended cabins and well-designed instrumentation and controls. These designs are not likely to become common in countries such as India in the near future because of economic reasons.

Tractors do not have suspension systems and the vibration levels (particularly for those without suspended cabins) are high compared to other road vehicles (Bovenzi & Betta, 1994). The problem of tractor ride becomes more critical since the dominant natural frequencies of the tractor (1–7 Hz) lie within the most critical frequency range of human body *e.g.* human trunk and lumbar vertebra have a natural frequency of 4–8 and 4–5 Hz, respectively (Pope & Hansson 1992; Troup, 1978). Vibrations experienced by the driver at the tractor seat lie especially in this vulnerable range. Also, there is no attenuation of transmission of frequency in the lower frequency range up to 6 Hz (Chaffin & Andersson, 1990). Mechanical damage of body organs is frequency dependent because of induced strains in the tissues, whereas, physiological effects are not always correlated with frequency or with any other aspect of vibration (Chaffin & Andersson, 1990). Vibration transmission has been

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Notation

a	distance from front axle to body centre of gravity, m
a_w	frequency weighted accelerations, $\mathrm{m\,s^{-2}}$
b	distance from rear axle to body centre of gravity, m
$[C]$	viscous damping of tractor-operator system, $\mathrm{kN\,s\,m^{-1}}$
c	viscous damping coefficient, $\mathrm{kN\,s\,m^{-1}}$
$[D]$	tyre damping matrix, $\mathrm{kN\,s\,m^{-1}}$
d	displacement, m
$[F]$	tyre stiffness matrix, $\mathrm{kN\,m^{-1}}$
H	transfer function
h_a	ground to axle centre of gravity, m
h_b	ground to body centre of gravity, m
h_p	ground to front axle pivot, m
i	$\sqrt{-1}$
I	inertia, $\mathrm{kg\,m^2}$
$[K]$	stiffness matrix of tractor-operator system, $\mathrm{kN\,m^{-1}}$
k	stiffness coefficient, $\mathrm{kN\,m^{-1}}$
l_X	longitudinal distance from centre of gravity to seat centre, m
l_Y	distance from centre of gravity to seat centre perpendicular to yaw axis, m
l_Z	vertical distance from centre of gravity to seat centre, m
M	tractor component mass, kg
$[M]$	mass matrix of tractor-operator system, kg
m	body part mass, kg
r	radius of tyre, m
S	spectral density, $\mathrm{m^2\,s^{-4}\,Hz^{-1}}$
T_l	lower boundary limit of time exposure, h
T_u	upper boundary limit of time exposure, h
t	wheel half-track, m
u	input displacement, m
w	wheel base of tractor, m
z	vertical displacement, m
ω	angular frequency of input excitation, $\mathrm{rad\,s^{-1}}$
κ	wave number, $\mathrm{rad\,m^{-1}}$

Subscripts

a	axle
ab	abdomen
b	tractor body
ba	back
di	diaphragm
f	front tyre ($n = 1, 2$)
he	head
L	left track
n	tyre number
pe	pelvis
R	right track
r	rear tyre ($n = 3,4$)
se	seat
tb	torso-back
th	thorax
to	torso
X	longitudinal direction
Y	lateral direction
Z	vertical direction
υ	degree of freedom
θ	pitch
ϕ	roll
ψ	yaw

reported to cause back problems because of tissue failure or from metabolic interference, or a combination of both.

Existing studies (Sorainen *et al*., 1998; Gerke & Hoag, 1981; Futatsuka *et al*., 1998) on tractor drivers either deal with vibration measurements and comparison of these with International Standard Organisation health standards (ISO 1985, 1997) or concentrate on the effect of vibrations on health. Very rarely do studies (Sandover *et al*., 1994; Boshuizen *et al*., 1990) combine both aspects. Even in vibration measurement studies on tractors without suspension the rating of the tractors is either not mentioned or different from those used in LICs. Vibration measurements were therefore done in field conditions on three suspension-less tractors of different power rating. An existing mathematical model was used to assess the vibrations due to a standard track with known power spectral density (PSD). Measured vibrations and simulated vibrations with the model were compared with ISO standards. These results were used to determine if the mathematical model of the tractor could be used to predict the severity of tractor vibrations in the absence of experimental data. A medical survey was done in a village on 50 tractor- and 50 non-tractor-driving farmers. This paper is thus an attempt to assess the vibration exposure, to compare this exposure with international norms and to determine the health status of tractor-driving farmers.

2. Objectives

There are three objectives: (1) to use a mathematical model of tractor and operator to determine the vibration exposure at seat level; (2) to measure and evaluate the level of whole-body vibrations transmitted to the tractor driver on different terrains; and (3) to examine whether tractor-driving farmers are at a greater risk of spinal damage than non-tractor-driving farmers, by comparing clinical and magnetic resonance imaging (MRI) data.

3. Methodology

3.1. *Development of mathematical model of tractor operator*

To enable seat vibrations to be studied, tractors have been modelled as a system of rigid bodies by various authors. The degrees of freedom in the model varied from one to 11 depending on complexity of the model. Initial models represented the tractor as a single lumped mass system and did not include the rotational masses. Later models included the effect of rotations and also modelled different components such as axles and tyres. The terrain inputs to these models also varied from periodic to random. A random profile commonly used for simulation purpose is the farm track presented in ISO 5008 (1979). The measured and predicted tractor vibrations at seat level were not close in different studies because of different parameters, such as deformability of terrain, improper representation of tyre stiffness or tyre characteristics. More recently, a model with tyres represented by dashpots and springs, placed in parallel for horizontal direction, was developed (Crolla *et al.*, 1990) and reported a close match between predicted and measured values. This model can be combined with a tractor operator model (Patil *et al.*, 1977). In the operator model, all body parts are connected to each other by some joints and linkages. These joints and links have specific characteristics, which can be non-linear. Simulation results with linear and non-linear characteristics did not demonstrate much difference (Wan & Schimmels, 1997). Therefore, a linearized human body model reported by Patil *et al.* (1977) is used in the study. This will be used in future to determine the vibration levels at various parts of the body.

The total degrees of freedom of the tractor-operator model are 19, the tractor having 11 and the human body-seat having eight degrees of freedom. The tractor degrees of freedom include six degrees of freedom for the tractor body, namely: vertical, longitudinal and lateral motion, pitch, roll and yaw, with one degree of freedom for the tractor axle, *i.e.* roll; and one rotational degree of freedom for each tyre. The details of the equations of motion are given by Crolla *et al.* (1990) and they refer to an inertial reference frame with the origin at the tractor's body mass centre. The operator model (*Fig. 1*) is a linearized form of the human body and has seven anatomical parts (Patil *et al.*, 1977). The body was connected to the tractor by a seat presented by Patil *et al.* (1977). Second-order terms and products of inertia were neglected. The model was therefore linear and results can be determined in the frequency domain. All the parameters used for tractor model are given in Appendix A. The dimensions of the tractors are available readily in the literature (Ministry of Agriculture, 1997) and also from the manufacturers. The inertia values for the pitch direction were obtained experimentally by finding the time period of oscillations on a compound pendulum. The roll and yaw inertia values were approximated by comparing the mass and dimensions of the Indian tractors with those available in the literature. Tyre stiffness and damping (which could not be obtained experimentally from available infrastructure facilities) were also taken from contemporary literature (Crolla *et al.*, 1990).

The tractor-operator dynamic equations can be written in matrix form as follows:

$$[M]\{\ddot{d}\} + [C]\{\dot{d}\} + [K]\{d\} = [D]\{\dot{u}\} + [F]\{u\} \quad (1)$$

where M is the mass matrix, C is the viscous damping matrix, K is the stiffness matrix and d is a column matrix of displacement of various points on a tractor. The right-hand side (RHS) represents the forces due to ground excitation at the four tyres; D and F include effect of tyre damping and stiffness, respectively, and u is a column matrix of input displacements at different tyres. The left-hand side (LHS), M, C and K are 19 by 19 matrices. The RHS has 19 rows and 4 columns corresponding to the 19 degrees of freedom in the model and four inputs at the wheels.

For a linear system, a direct linear relationship between input and output exists. The tractor characterized by its transfer function modifies the inputs representing a surface profile to the output representing the resulting vibration of the tractor. The transfer function $H(\omega)$ is defined as the ratio of the output to the input under steady-state conditions at angular frequency ω and here it is given by

$$[H(\omega)] = \{-\omega^2[M] + \mathrm{i}\omega[\mathrm{C}] + [K]\}^{-1}\{\mathrm{i}\omega[D] + [\mathrm{F}]\} \quad (2)$$

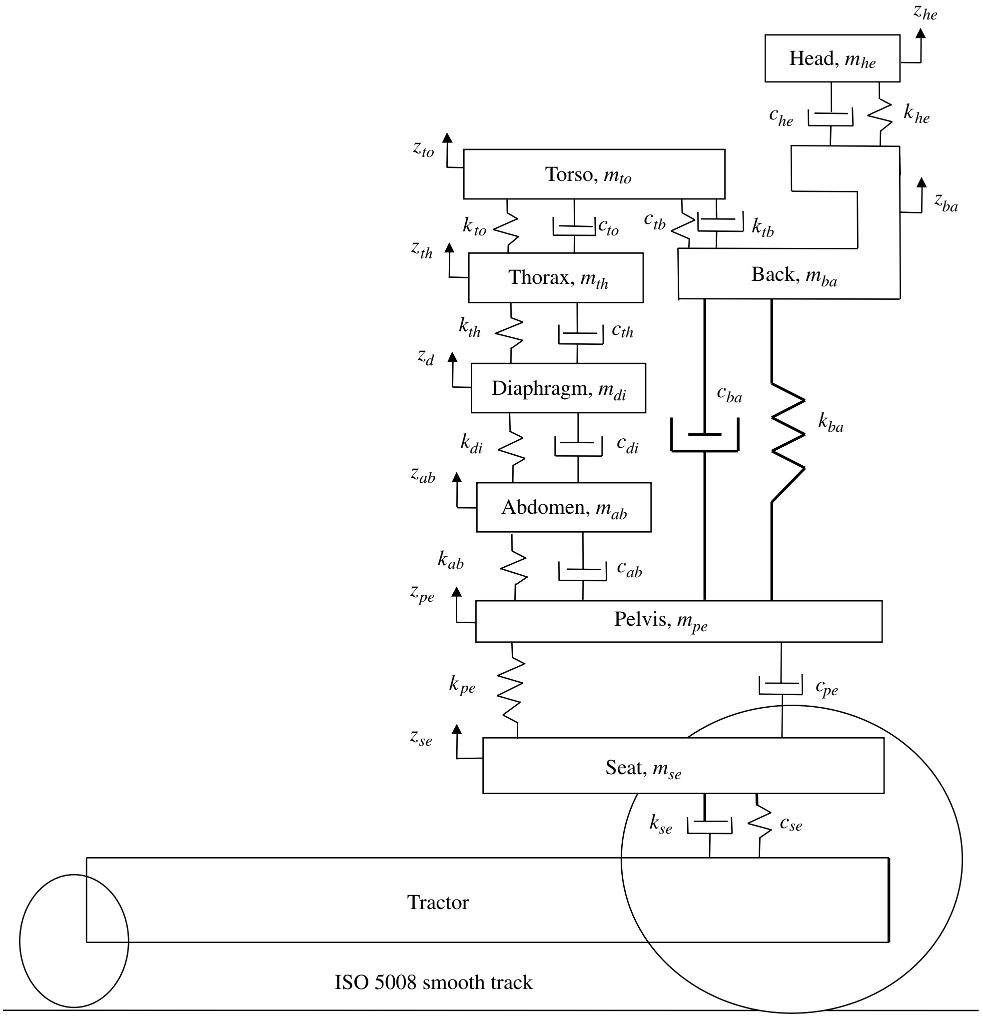


Fig. 1. Tractor-operator model; z, vertical displacement; c, damping; k, stiffness; and m, mass; subscripts indicate first two letters of the related body part

where i is $\sqrt{-1}$. The earlier tractor models used a periodic input to the tyres. The periodic input is simple to work with and also provides a basis for comparative evaluation of various designs of vehicles. However, when studying the actual ride behaviour of vehicles, they are of little use, since surface profiles have rarely a simple periodic form. Random profiles represent actual conditions better. In ISO 5008 (1979) a random farm track was defined. One of these tracks has been used here as input for the tractor-operator vibration analysis.

Methods for measuring and reporting the whole-body vibrations to which the operator of an agricultural wheeled tractor is exposed are also specified in ISO-5008 (1979). One of the smoother tracks from this standard is used for this study. The elevations of this track are defined at 160 mm intervals for both sides. The input to the tractor in terms of power spectral density (PSD) is obtained by doing a fast Fourier transform (FFT) of elevation of the track.

2. Text section

Discrete displacement PSD, $S_\upsilon(\omega)$ at the centre of gravity (CG) is given as (Dodds & Robson, 1973).

$$\begin{aligned} S_\upsilon(\omega) = (&[H^*_{\upsilon,1}H_{\upsilon,1} + H^*_{\upsilon,3}H_{\upsilon,3} + H^*_{\upsilon,3}H_{\upsilon,1}\mathrm{e}^{\mathrm{i}\kappa w} \\ &+ H^*_{\upsilon,1}H_{\upsilon,3}\mathrm{e}^{-\mathrm{i}\kappa(a+b)}]_\omega S_L(\omega) + [H^*_{\upsilon,2}H_{\upsilon,2} \\ &+ H^*_{\upsilon,4}H_{\upsilon,4} + H^*_{\upsilon,4}H_{\upsilon,2}\mathrm{e}^{\mathrm{i}\kappa w} + H^*_{\upsilon,2}H_{\upsilon,4}\mathrm{e}^{-\mathrm{i}\kappa(a+b)}]_\omega \\ &\times S_R(\omega) + [H^*_{\upsilon,1}H_{\upsilon,2} + H^*_{\upsilon,3}H_{\upsilon,4} + H^*_{\upsilon,1}H_{\upsilon,4}\mathrm{e}^{-\mathrm{i}\kappa w} \\ &+ H^*_{\upsilon,3}H_{\upsilon,2}\mathrm{e}^{\mathrm{i}\kappa(a+b)}]_\omega S_{LR}(\omega) + [H^*_{\upsilon,2}H_{\upsilon,1} + H^*_{\upsilon,4}H_{\upsilon,3} \\ &+ H^*_{\upsilon,4}H_{\upsilon,1}\mathrm{e}^{\mathrm{i}\kappa w} + H^*_{\upsilon,2}H_{\upsilon,3}\mathrm{e}^{-\mathrm{i}\kappa(a+b)}]_\omega S_{RL}(\omega)) \quad (3) \end{aligned}$$

where $[H_{\upsilon,n}]_{\omega}$ is the complex transfer function calculated above for the ω^{th} frequency; a is the distance between front axle and CG; b is the distance between rear axle and CG, w is wheel base, i is $\sqrt{-1}$; the degrees of freedom υ vary from 1 to 19 and the first six terms pertain to the longitudinal direction X , lateral direction Y, vertical direction Z, roll Φ, pitch θ and yaw Ψ and values for n from 1 to 4 represent tyres to which input in the form of track elevation is applied. The asterisks (*) indicate complex conjugate, S_L, S_R are auto-spectral densities of left and right tracks, S_{LR}, S_{RL} are cross spectral density of left–right and right–left track; and κ is a wave number in rad m^{-1}.

To translate these motions from CG to seat, the following relations are used:

$$S_{X-seat}(\omega) = S_X(\omega) + l_Y{}^2 S_{\phi}(\omega) + l_Z{}^2 S_{\psi}(\omega)$$

$$S_{Y-seat}(\omega) = S_Y(\omega) + l_X{}^2 S_{\theta}(\omega) + l_Z{}^2 S_{\psi}(\omega)$$

$$S_{Z-seat}(\omega) = S_Z(\omega) + l_X{}^2 S_{\theta}(\omega) + l_Y{}^2 S_{\phi}(\omega) \qquad (4)$$

where: $S(\omega)$ with subscript X, Y, Z, Φ, θ, Ψ represent spectral density in the longitudinal direction, lateral direction, vertical direction, roll, pitch and yaw at centre of gravity; $S_{X,Y,Z-seat}(\omega)$ represent spectral density at seat in longitudinal, lateral and vertical directions; l_X, l_Y and, l_Z represent longitudinal, lateral and vertical distances from centre of gravity to seat centre point. The displacement PSD was converted into acceleration PSD by multiplying with ω^4 and then integrated over entire frequency range for finding root mean square acceleration. Weighting factors (ISO, 1997) were incorporated in the output PSDs to get ISO-weighted root mean square (rms) acceleration values.

The vibration accelerations were compared with two different health standards. The first standard, ISO (1985) prescribes various health limits while the second standard, ISO (1997) gives health caution zone limits.

For ISO (1985), rms accelerations at the interface of seat and operator in orthogonal coordinates were compared with the limits of the standard in different one-third-octave bands. The limits are given in terms of (1) reduced comfort boundary (RC) for preservation of comfort, (2) fatigue decreased proficiency boundary (FDP) for the preservation of working efficiency and (3) exposure limit (EL) for preservation of health and safety. The values are different for horizontal and vertical vibrations. The reduced comfort boundary is obtained by dividing the fatigue decreased proficiency limit by 3·15, exposure limits are obtained by multiplying the proficiency limits by 2.

A second comparison of the highest ISO (1997) frequency weighted accelerations a_w with ISO (1997) was done. In this standard, a health guidance zone is presented which has an upper boundary and a lower boundary limit. Overall vibration acceleration above upper boundary indicates the likeliness of health risks and below the lower boundaries indicates no health effects. With values of 6 and 3 m s^{-2} as upper and lower boundary limits of caution zone, the values of upper T_u and lower boundary limit T_l time exposure were calculated by using the following relation:

$$T_u = T_6[6/a_w]^2 \qquad (5)$$

and

$$T_l = T_3[3/a_w]^2 \qquad (6)$$

where T_u and T_l are exposure durations at the upper and lower limits of the caution zone, T_6 and T_3 are 6 and 3 m s^{-2} rms acceleration between 1 and 10 min of the health caution zone (Griffin, 1998).

All these steps were incorporated in a computer code, for simulating three different tractors of 14·9, 26·1 and 37·3 kW, respectively all operating on ISO 5008 track at different velocities ranging from 8 to 18 km h^{-1} with steps of 2 km h^{-1}.

3.2. *Tractor vibration measurements*

A tri-axial accelerometer from B&K Deltatron (Type 4504) was mounted on the tractor seat to register the vibration levels as predefined in ISO 5008 (1979) standard. In this way, acceleration up to a maximum of ±7500 m s^{-2} in the frequency range from 1 to 1000 Hz could be measured in all the three directions. All signals are conditioned with a four-channel Deltatron conditioning amplifier (type 2693) with band-pass filter at selected cut-off frequencies between 0·1 Hz and 0·1 kHz, respectively. An external power supply was made for the conditioning amplifier using two 12 V, seven Ah batteries connected in series. The observations were recorded, on three individual channels at a sampling rate of 1·33 kHz each, on a laptop computer equipped with a PCMCIA data acquisition card with signal conditioning daughter board. The experimental measurements were conducted both on farm terrain and on the transportation track of village paths and paved city roads with 14·9, 26·1 and 37·3 kW tractors at constant tyre inflation pressure (3·4 kg cm^{-2} for front tyres and 1·25 kg cm^{-2} for rear tyres). Each observation of the experiment took 20 kbytes of memory and required approximately 6–7 s to collect data.

Power-spectral density of observed values was calculated by taking fast Fourier transform (FFT) of values in respective directions. Weighting (ISO, 1997) was incorporated in the accelerations. Root mean square values in respective one-third-octave band and ISO (1997) weighted overall rms values of accelerations were calculated for comparison with ISO 2631-1, 1985 and 1997 standards, respectively. The procedure followed for these comparisons was similar to that explained in Section 3.1.

3.3. *Health studies*

Health effects of exposure to whole-body vibrations (WBV) have been studied by investigators with and without control groups not exposed to vibrations. The case-control studies showed higher reporting of low back pain and radiological symptoms in tractor drivers compared to the control group. Stiles *et al.* (1993) suggested that back ailments among agricultural workers were widespread because of several confounding factors including the high level of whole-body vibrations, the large amount of manual work and the twisting action of drivers during tractor driving.

Seidel and Heide (1986) suggested that experimental and control groups should be characterized by exact matching with respect to age, sex, profession and exposure conditions and if possible with their 'way of life'. Hulshof and Zanten (1987) reviewed the studies on different whole-body exposure on the basis of exposure data, effect data, study design and methodology. They concluded that most studies fail to control confounding factors, such as age, sitting for long hours, lifting of heavy loads and climatically poor working conditions. On the basis of this, they recommended retrospective cohort and case-control studies.

In the present health study, these factors were incorporated by choosing experimental and control groups with matching age, sex, exposure and 'way of life'. Fifty experienced subjects were selected from two villages, 50 km from Delhi. All tractor drivers selected, satisfied the following criteria: Minimum tractor-driving experience of 5 years; age group 25–45 years; minimum land holding of 2 h; not suffering from any disease except back related; not involved in regular travel by any means of transport; and willingness to participate in the study. Information was also collected from each subject on age; education; occupation(s), including number of years of active farming and tractor driving (for study group); tractor details and hours of driving experience in a year (for study group); details of land holding; food habits; and smoking and alcohol intake. The 50 subjects for the control group were chosen using the same selection criteria, except that they did not drive a tractor.

Details of vibration exposure and manual work performed by both the groups were observed in terms of transportation mode occasionally used, usage frequency and duration of use; farm-related manual work (spade work in different farm activities and carrying of farm inputs and produce); and any other physical activity.

All participants were interviewed on their health history over the previous 2 weeks, over the previous 1 year and from birth, respectively. They were specifically questioned regarding back problems, including duration and frequency of back complaints, treatment for backache, bed rest because of back pain, radiating pain, severity of back pain and sensory loss.

The physical examination included a general check of cardio-vascular, gastro-intestinal, genito-urinary and neurological systems; lungs, extremities, spine; check for the presence of any abnormal masses in abdomen and collection of anthropometric dimensions.

All the participants underwent magnetic resonance imaging (MRI) of the lower back. An orthopaedic surgeon, radiologist, and a neurosurgeon evaluated the randomly coded scans. A separate performa was designed to record the results of the evaluation. Details of the medical evaluation are given in an earlier publication (Kumar *et al*., 1999).

4. Results

4.1. *Vibration study with tractor-operator model*

4.1.1. *Predicted root mean square accelerations*

The longitudinal direction rms accelerations remained lower than the 4 h fatigue decreased proficiency limit in all tractor-velocity combinations. In the lateral direction, rms accelerations exceeded the 4 h FDP with increased velocity but remained lower than the 4 h exposure limit in all tractor velocity combinations. In the vertical direction rms acceleration values were high, so comparisons with 2·5 and 4 h exposure limits were made (*Fig. 2*). For the 14·9 kW tractor, 2.5 h EL was exceeded at 8, 16 and 18 km h^{-1}, 4 h EL was exceeded at all the velocities. For the 26·1 kW tractor, the rms acceleration values remained lower than 2·5 h EL except at 12 and 18 km h^{-1} where rms acceleration was equal to or exceeded 2·5 EL. For the 37·3 kW tractor, the rms acceleration levels remained lower than 4 h EL up to 12 km h^{-1} velocity. Above 12 km h^{-1} the value exceeded 4 h EL but remained lower than 2·5 h EL.

A comparison of ISO-weighted rms acceleration with the ISO 2631-1 (1997) health caution zone, is given in Table 1. The accelerations in the vertical direction were highest at all velocity tractor combinations, so the comparison of health caution zone was done for vertical direction ISO-weighted accelerations. The table shows the effect of velocity on upper time limit T_u. As the velocity increases upper time limit decreases. Upper time

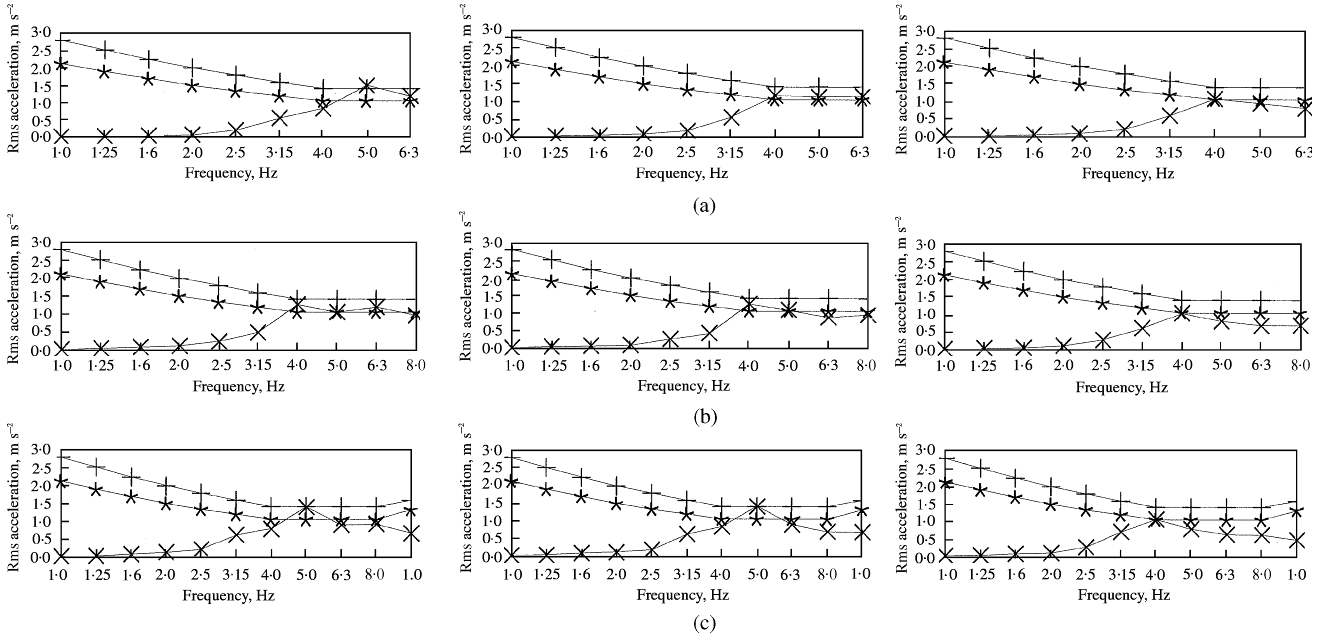


Fig. 2. Comparison of predicted vertical root mean square (rms) accelerations with ISO 2631-1 (1985) limits at three velocities: (a) 8; (b) 10; and (c) 12 km h^{-1}; on ISO 5008 track for a 14·9 kW (left), a 26·1 kW (centre) and a 37·1 kW tractor (right): +, 2·5 h exposure limit; ✶, 4 h exposure limit; ×, predicted values

limit varied from 0·62 to 0·42 h at 8–18 km h^{-1} for 14·9 kW tractor. Similarly, for the 26·1 kW tractor, the variation observed was from 0.68 to 0.48 h and in 37.3 kW from 0.94 to 0.63 h at 8–18 km h^{-1} speed. This also shows that the higher the power rating of tractor, the higher was the upper time limit. In all cases, the acceleration values in vertical direction varied between 2·5 and 3·8 m s^{-2}. In the lateral direction, the acceleration

Table 1
Overall ISO-weighted root mean square (rms) values for three axes (*Z*, vertical; *Y*, lateral; and *X*, longitudinal) and vector sum values of predicted accelerations and comparison with ISO 2631-1 Health Guidance Caution Zone limit (ISO, 1997)

Tractor, kW	*Velocity, km h^{-1}*	*ISO-weighted rms acceleration, m s^{-2}*			*Vector sum, m s^{-2}*	*Health limit, h*	
		Z	*Y*	*X*		*Upper*	*Lower*
14·9	8	3·10	1·08	0·56	3·54	0·62	0·16
	10	3·29	1·21	0·57	3·79	0·55	0·14
	12	3·24	1·25	0·56	3·76	0·57	0·14
	14	3·41	1·55	0·61	4·13	0·52	0·13
	16	3·76	1·73	0·68	4·57	0·42	0·11
	18	3·80	1·86	0·76	4·73	0·42	0·10
26·1	8	2·96	0·96	0·48	3·32	0·68	0·17
	10	3·08	1·07	0·47	3·49	0·63	0·16
	12	3·17	1·18	0·51	3·65	0·60	0·15
	14	3·12	1·41	0·54	3·77	0·62	0·15
	16	3·33	1·54	0·56	4·04	0·54	0·14
	18	3·55	1·64	0·63	4·32	0·48	0·12
37·3	8	2·53	0·92	0·47	2·91	0·94	0·23
	10	2·55	1·02	0·50	3·01	0·92	0·23
	12	2·64	1·30	0·51	3·29	0·86	0·22
	14	2·73	1·37	0·56	3·43	0·81	0·20
	16	2·86	1·45	0·54	3·59	0·73	0·18
	18	3·08	1·6	0·58	3·89	0·63	0·16

values for the three tractors were within 1·0–1·3 m s^{-2} at velocities up to 12 km h^{-1}. At velocities greater than 14 km h^{-1} ISO-weighted rms acceleration for 14.9 kW tractor was approximately 0.3 m s^{-2} larger as compared to the other two tractors. In 35 and 37·3 kW tractors, in the longitudinal direction the acceleration values were quite close but lower than the 14·9 kW tractor. In all cases, the rms acceleration value increases with velocity.

4.2. *Vibration measurements*

Tractors of 14·9, 26·1 and 37·3 kW were used for measurements of vibration on farm and transportation tracks. The farm track had been secondary tilled after harvesting and was reasonably level. The transportation track included village paths and paved roads. The village paths cut across farms and are used by all forms of traffic *e.g.* pedestrians, tractors, bullock carts. The city-paved roads are used for transportation purposes from villages to cities.

4.2.1. *Measured root mean square accelerations*

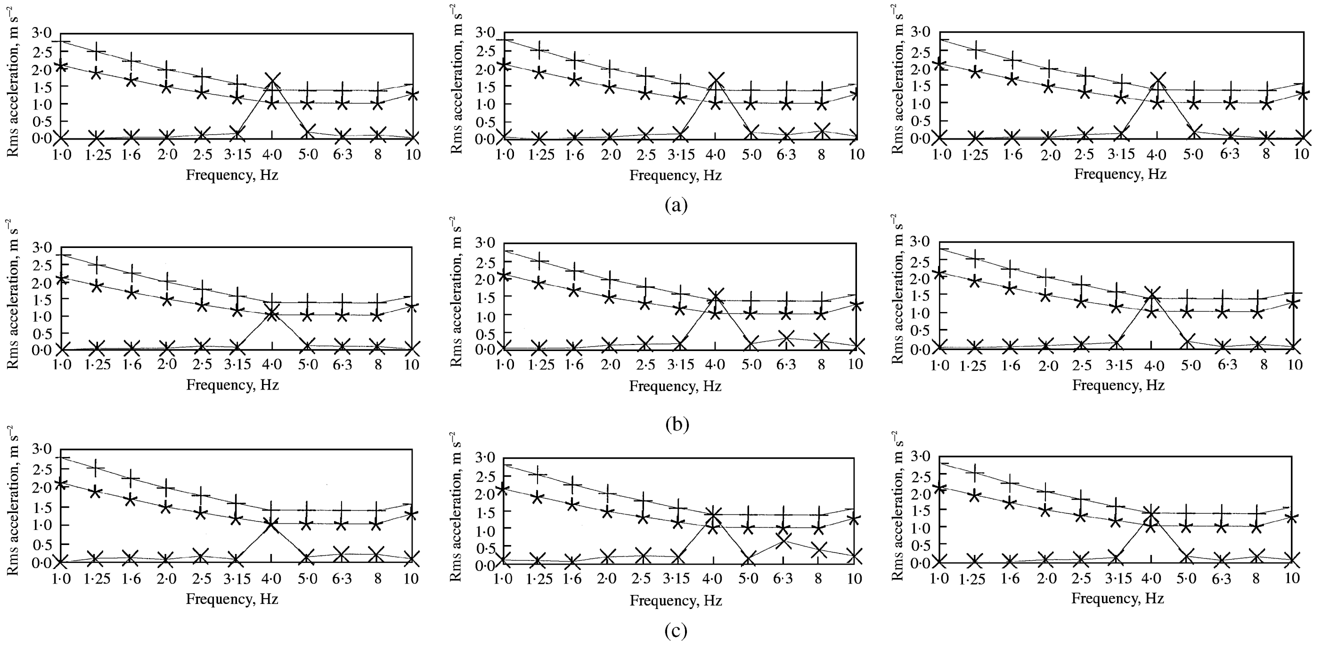
Comparisons of rms accelerations in the one-third-octave band were done with a 4 and 8 h FDP as described in ISO 2631-1 (1985). In all the tractor–terrain combinations lateral and longitudinal direction rms accelerations remained lower than or equal to 4 h FDP in most of the observations. In the vertical direction, 4 h FDP values were exceeded, so a comparison with EL was done (*Fig. 3*). In case of a 14·9 kW tractor the 2·5 h EL was exceeded in all terrain–velocity combinations.

With a 26·1 kW tractor, farm terrain rms accelerations were approximately equal to 4 h EL. When used on village paths, rms accelerations exceeded the 4 h EL but were lower than or equal to 2·5 h EL. With road use, rms accelerations were lower than 2·5 EL for all terrain–velocity combination except at lowest velocity of 8 km h^{-1} where 2·5 h EL was exceeded.

With a 37·3 kW tractor, on farm terrain, vertical direction rms acceleration values were approximately equal to or lower than 4 h EL except at 14 km h^{-1} where rms values exceeded 4 h EL and were slightly lower than 2·5 h EL. On the village path at 10, 12 km h^{-1} velocity, rms values were lower than the 4 h EL. At 8 km h^{-1}, values exceeded 4 h EL but remained lower than 2·5 h EL. On the paved road, rms values remained lower than 4 h EL except at 12 km h^{-1} where values exceeded 4 h EL but remained lower than 2·5 h EL.

4.2.2. *Overall weighted root mean square accelerations*

The values of different observations for all the tractors are summarized in Table 2 for comparison with health caution zone of ISO 263-1 (1997). The results show that the maximum upper limit of the health caution zone was



(a)

(b)

(c)

Fig. 3. Comparison of measured vertical root mean square (rms) accelerations with ISO 2631-1 (1985) limits at 8 km h^{-1} for a: (a) 14·9; (b) 26·1; and (c) 37·3 kW tractor; on farm (left), village path (centre) and paved road (right): +, 2·5 h exposure limit; ★, 4 h exposure limit, ×, measured values

Table 2
Overall ISO-weighted root mean square values for three axes (*Z*, vertical; *Y*, lateral; and *X*, longi tudinal) and vector sum values of measured accelerations and comparison with ISO 2631-1 Health Guidance Caution Zone limit (ISO, 1997)

Terrain	*Tractor, kW*	*Velocity, $\mathrm{km\,h^{-1}}$*	*Root mean square acceleration $\mathrm{m\,s^{-2}}$*			*Vector sum, $\mathrm{m\,s^{-2}}$*	*Health limit, h*	
			Z	*Y*	*X*		*Upper*	*Lower*
Road	14·9	8	1·80	0·37	0·22	1·90	1·85	0·46
		10	1·80	0·41	0·39	1·97	1·85	0·46
		12	1·91	0·50	0·70	2·26	1·64	0·41
		14	1·95	0·78	0·73	2·46	1·58	0·39
	26·1	8	1·63	0·53	0·20	1·81	2·26	0·56
		10	1·44	0·72	0·27	1·80	2·89	0·72
		12	1·42	0·77	0·37	1·86	2·98	0·74
		14	1·67	0·98	0·66	2·35	2·15	0·54
	37·3	8	1·51	0·72	0·15	1·83	2·63	0·66
		10	1·36	0·58	0·39	1·67	3·24	0·81
		12	1·33	0·63	0·47	1·73	3·39	0·85
		14	2·15	1·20	1·04	3·09	1·30	0·32
Village path	14·9	8	1·83	0·60	0·53	2·14	1·79	0·45
		10	1·87	0·58	0·72	2·27	1·72	0·43
		12	1·95	0·99	1·03	2·79	1·58	0·39
		14	2·11	1·17	0·95	2·98	1·35	0·34
	26·1	8	1·71	0·84	0·37	2·14	2·05	0·51
		10	1·53	0·75	0·40	1·94	2·56	0·64
		12	1·65	0·90	0·55	2·21	2·20	0·55
		14	2·06	1·14	1·02	2·97	1·41	0·35
	37·3	8	1·76	0·81	0·43	2·18	1·94	0·48
		10	1·70	0·79	0·74	2·28	2·08	0·52
		12	1·93	0·84	0·72	2·47	1·61	0·40
		14	2·92	1·53	1·58	4·24	0·70	0·18
Farm	14·9	8	1·78	0·51	0·62	2·11	1·89	0·47
		10	1·82	0·61	0·69	2·23	1·81	0·45
		12	1·92	0·85	0·90	2·58	1·63	0·41
		14	2·28	1·01	1·01	3·03	1·15	0·29
	26·1	8	1·25	0·65	0·24	1·58	3·84	0·96
		10	1·37	0·70	0·39	1·77	3·20	0·80
		12	1·38	0·78	0·57	1·93	3·15	0·79
		14	1·77	1·04	0·89	2·61	1·92	0·48
	37·3	8	1·30	0·58	0·33	1·60	3·55	0·89
		10	1·64	0·76	0·66	2·16	2·23	0·56
		12	1·79	1·05	0·94	2·66	1·87	0·47
		14	2·99	1·70	1·79	4·57	0·67	0·17

3·55, 3·84 and 1·89 h on farm terrain with 37·3, 26·1 and 14·9 kW tractors, respectively. The 3 h upper limit of the health caution zone was observed only in the 37·3 kW tractor on road and farm, while in the 26·1 kW tractor, values remained below 3 h except on farm terrain and in the 14·9 kW tractor, the maximum value was 1·89 h. This also showed that upper limit of the health caution zone is lower than 3 h with most tractor–terrain combinations.

Table 2 indicates that the velocity of the tractor and the type of terrain do not have a significant effect on overall rms accelerations in any directions for the tractors on which measurements were done. However, with the 26·1 and 37·3 kW tractors, lower rms accelerations were observed in the vertical direction as compared to the 14·9 kW tractor. The rms accelerations in the lateral and longitudinal directions were almost similar for the three tractors.

4.3. *Comparison of vibration magnitude between tractor-operator model and experimental measurements*

The tractor-operator model was used to calculate vibration magnitudes of different tractors at different velocities on ISO 5008 (1979) smooth terrains. Measurements of vibrations were made on similar tractors on different terrains (farm, village path and paved road) for which PSD was not known. A comparison of the model and the measurement values of PSD peaks, frequency at which peak PSD occurred and rms values were considered.

4.3.1. *Power-spectral density peak values*

Table 3 gives values of peak PSD and the frequencies at which peaks appear. In the 14.9 kW tractor predicted peak values were in the range of 9–13 $\mathrm{m^{2}\,s^{-4}\,Hz^{-1}}$ in the vertical direction, 1–4 $\mathrm{m^{2}\,s^{-4}\,Hz^{-1}}$ in the lateral direction and 0·2–0·4 $\mathrm{m^{2}\,s^{-4}\,Hz^{-1}}$ in the longitudinal direction. In the case of measured values, PSD peaks were in the range of 15–16 $\mathrm{m^{2}\,s^{-4}\,Hz^{-1}}$ in the vertical direction for all the terrains, 0·3–0·7 $\mathrm{m^{2}\,s^{-4}\,Hz^{-1}}$ in the lateral direction and 0·05–3·5 $\mathrm{m^{2}\,s^{-4}\,Hz^{-1}}$ in the longitudinal direction for farm terrain. On village paths, PSD peak values were in the range of 0·25–1·0 $\mathrm{m^{2}\,s^{-4}\,Hz^{-1}}$ in the lateral and 0·14–1·5 $\mathrm{m^{2}\,s^{-4}\,Hz^{-1}}$ in the longitudinal direction. On paved roads, PSD peak values were in the range of 0·1–0·5 $\mathrm{m^{2}\,s^{-4}\,Hz^{-1}}$ in the lateral and 0·03–0·47 $\mathrm{m^{2}\,s^{-4}\,Hz^{-1}}$ in the longitudinal direction.

Table 3

Power-spectral density peak values and frequency at which peak appears in predicted and measured values; *Z*, vertical; *Y*, lateral; and *X*, longitudinal

Tractor, kW	*Velocity km h^{-1}*	*Direction*	*Predicted values*		*Measured values*					
					Farm		*Village path*		*Paved road*	
			PP	*FR*	*PP*	*FR*	*PP*	*FR*	*PP*	*FR*
14.9	8	Z	9·20	4–5	15·63	4–5	15·55	4–5	15·62	4–5
		Y	1·01	2–3	0·33	1–2	0·46	2–3	0·14	2–3
		X	0·38	3–4	0·78	2–3	0·14	1–2	0·03	2–3
	10	Z	10·57	4–5	15·59	4–5	15·07	4–5	15·53	4–5
		Y	3·65	2–3	0·32	1–2	0·25	2–3	0·17	2–3
		X	0·40	4–5	3·44	1–2	0·77	2–3	0·14	2–3
	12	Z	8·84	4–5	15·60	4–5	15·44	4–5	15·80	4–5
		Y	1·69	2–3	0·73	1–2	1·02	1–2	0·09	1–2
		X	0·20	3–4	1·05	1–2	1·43	1–2	0·54	2–3
	14	Z	12·96	4–5	14·69	4–5	14·93	4–5	14·68	4–5
		Y	3·98	2–3	0·62	1–2	0·67	4–5	0·57	2–3
		X	0·39	3–4	0·05	1–2	0·68	1–2	0·47	2–3
26·1	8	Z	11·50	6–7	7·03	4–5	12·81	4–5	12·79	4–5
		Y	0·85	2–3	1·67	4–5	2·84	4–5	3·11	4–5
		X	0·26	3–4	0·05	1–2	0·15	1–2	0·06	2–3
	10	Z	12·32	4–5	7·12	4–5	8·87	4–5	8·77	4–5
		Y	2·93	3–4	1·52	4–5	2·02	4–5	2·18	4–5
		X	0·21	3–4	0·01	2–3	0·08	3–4	0·03	2–3
	12	Z	12·29	4–5	5·92	4–5	9·31	4–5	8·25	4–5
		Y	1·93	3–4	1·35	4–5	2·42	4–5	2·21	4–5
		X	0·56	3–4	0·24	2–3	0·41	1–2	0·10	1–2
	14	Z	12·35	4–5	6·45	4–5	10·47	4–5	9·46	4–5
		Y	3·35	3–4	2·14	4–5	2·1	4–5	2·51	4–5
		X	0·52	4–5	0·55	2–3	0·73	1–2	0·29	1–2
37·3	8	Z	6·53	4–5	5·54	4–5	10·36	4–5	10·24	4–5
		Y	1·57	2–3	1·19	4–5	2·32	4–5	2·39	4–5
		X	0·30	3–4	0·17	1–2	0·20	2–3	0·01	4–5
	10	Z	5·68	4–5	5·41	4–5	4·30	4–5	3·92	4–5
		Y	1·39	3–4	0·99	4–5	0·83	4–5	1·00	4–5
		X	0·51	4–5	0·39	1–2	0·25	1–2	0·15	1–2
	12	Z	8·11	4–5	4·22	4–5	4·72	4–5	3·38	4–5
		Y	3·40	2–3	0·94	1–2	1·38	4–5	1·00	4–5
		X	0·50	3–4	0·75	3–4	0·50	1–2	0·28	1–2
	14	Z	9·54	4–5	4·97	4–5	7·01	6–7	5·33	4–5
		Y	3·80	2–3	1·89	4–5	2·14	1–2	1·77	4–5
		X	0·64	4–5	2·36	3–4	2·46	1–2	1·06	1–2

PP, peak power-spectral density value, $\mathrm{m^{2}\,s^{-4}\,Hz^{-1}}$; FR, frequency range, Hz

The frequency at which peaks appear was 4–5 Hz in the vertical direction and in the range of 2–5 Hz for the longitudinal and lateral directions for both measured and predicted vibrations.

Similar differences between the simulated and measured peak PSDs and the frequencies at which these peaks occur are also observed for 26·1 and 37·3 kW tractors as shown in Table 3.

4.3.2. *Overall weighted root mean square accelerations*

The predicted ISO-weighted rms acceleration in the vertical direction was higher than the measured values (*Fig. 4*). The predicted values of vertical rms at almost all velocities for all the tractors were between 1 and 1·5 $m\,s^{-2}$ higher than the experimental values. Only for the 37·3 kW tractor for velocities greater than 12 $km\,h^{-1}$ do the predicted rms acceleration values fall below the measured values. The lateral ISO-weighted rms values showed a similar trend, except that the difference between predicted and measured values was between 0·25 and 0·5 $m\,s^{-2}$. The longitudinal rms accelerations from the model were always below the measured values.

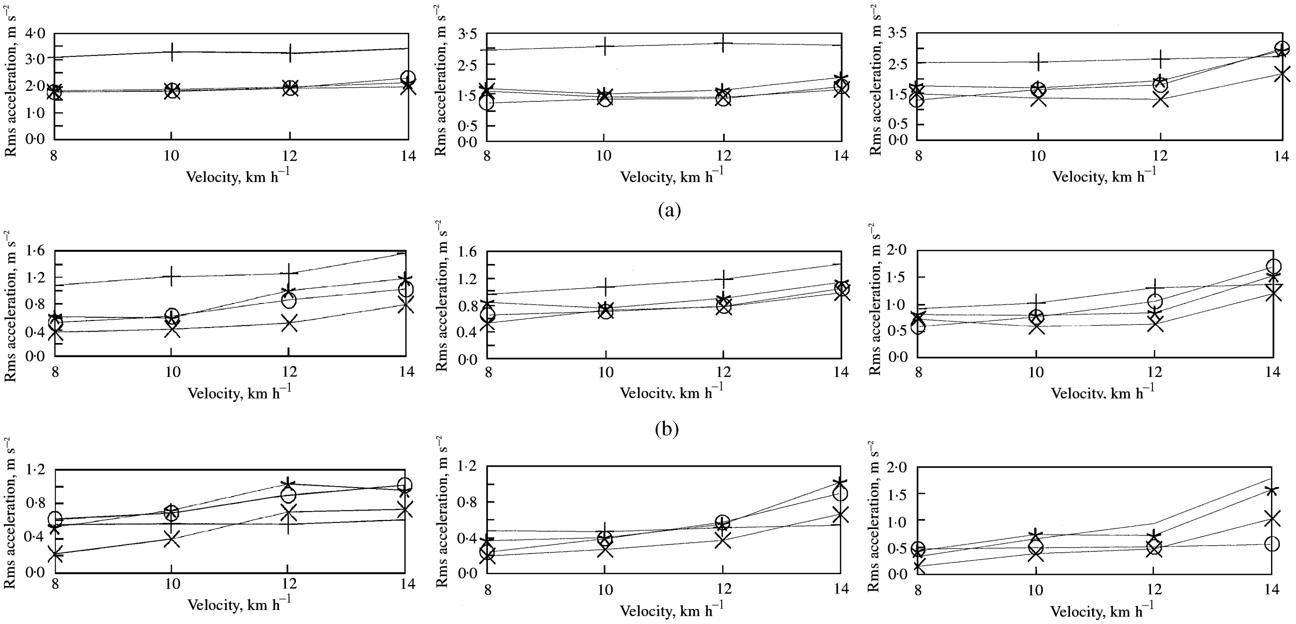
4.4. *Health studies*

Two groups were selected with the age of the subjects ranging from 25 to 45 years and having experience of farming and tractor-driving for more than 5 years. Details are tabulated in Table 4. Height, chest expansion and arm span were same for both the groups. Only abdominal girth and weight are statistically different in both groups at significance levels of 0·006 and 0·046. The tractor-driving farmers had larger waist size and were heavier.

The results show that tractor-driving farmers complain of low back pain more often than non-tractor-driving farmers. Clinical examination, however, did not reveal any significant differences between the two groups. Magnetic resonance imaging (MRI) evaluation of spines of tractor-driving farmers and non-tractor-driving farmers showed degenerative changes in both groups. MRI of both groups showed significant degenerative changes in 96% of participants for both groups. The evaluation of MRI images was done by three specialists (orthopaedic surgeon, neurosurgeon and radiologist) using a specially designed protocol to eliminate the subjective bias. The results show that there was no statistical difference in evaluation of MRI images of study and control group by the three specialists (Kumar *et al*., 1999).

4.5. *Driving hours and health status*

A survey was also conducted among tractor-drivers to estimate the tractor-driving hours on an annual basis. It



(a)

(b)

(c)

Fig. 4. ISO-weighted (ISO 2631-1, 1997) predicted root mean square (rms) accelerations on ISO 5008 track and measured rms accelerations on different terrains in: (a) vertical; (b) lateral; and (c) longitudinal directions; for a 14·9 (left), a 26·1 (centre) and a 37·1 kW tractor (right): +, predicted values; ★, road; ×, village path; O, farm

Table 4
Similarities and differences between study group and control group

Parameters	*Similarity/difference (P value*)*
Anthropometric dimensions	
Height	Similar (0·687)
Chest expansion	Similar (0·755)
Waist size	Different (0·006)†
Arm span	Similar (0·701)
Weight	Different (0·046)†
Education	Similar (0·690)
Dietary habits	
Food habits	Similar (> 0·005)
Smoking	Similar (0·234)
Alcohol intake	Similar(0·220)
Agricultural assets ownership	
Tractor-operated equipment	Different (< 0·005)
Bullock and bullock-operated implements	Different (< 0·005)
Milking animals	Similar (0·060)
Other equipment	Similar(> 0·050)
Family profile	Similar (> 0·050)
Transportation modes	Different (< 0·005)
Manual work	
Spade	Similar (0·488)
Carrying farm inputs and produce	Similar (> 0·050)
Assistance in manual work (family member and hired labour)	Similar (> 0·050)
Health problems in	
last 2 weeks	Different (0·001)†
last 12 month sentire life	Similar (0·202)
	Similar(0·027)
Musculoskeletal disorders	
Musculoskeletal complaints	Different (0·015)†
Regular back complaints	Different (0·010)†
Frequency and symptoms of back pain	Similar (0·040)
Sensory symptoms (numbness) in body parts	Different (0·047)†
Posture/activity-related problems	Similar (> 0·050)
Clinical investigation	Similar (> 0·050) Except knee jerk (0·023)†
MRI evaluation	Similar (> 0·050)

*Value of probability
†Higher in tractor-driving farmers (study group)

was quite difficult to assess the exposure as tractors are not only confined to single farms but are also hired out to other farms for both on-the-farm and off-the-farm operations. The analyses revealed that driving hours per annum were in the range of 100–5000 with a median of 1000 and a standard deviation of 757 h.

5. Discussion

5.1. *Tractor vibration magnitude*

5.1.1. *Root mean square accelerations*

In the present study, the experiments were conducted at the farms and transportation terrains in the same villages where the tractor driver health studies were conducted.

For all tractors predicted ISO-weighted rms acceleration values were higher in the vertical direction. The discrepancy between predicted and measured values was because of basic differences in the terrains used for simulation and measurement. The profile of ISO 5008 (1979) smooth track had higher elevations (as compared to farm/transportation track) and was supposed to be non-deformable, whereas in practice, terrains are deformable especially on the farm.

When the vibration values of the present study were compared with previous studies it was observed that for these studies similar tractor ratings were not available, different terrains had been used and also operational conditions (*e.g.* attached implements) were different. However, acceleration values for tractors similar in weight to the present study tractors (Matthews, 1966; Lines *et al.*, 1984; Stayner & Bean, 1975, Crolla *et al.*, 1990) were in the vicinity of the observed values in the study.

5.1.2. *Vector sum accelerations*

The vector sum values of measured accelerations on the farm were 1·96–3·03 m s^{-2} on the 14·9 kW tractor, 1·81–2·97m s^{-2} on the 26·1 kW tractor and 1·6–4·57 m s^{-2} on the 37·3 kW tractor on all terrains at 8–14 km h^{-1}. Using the model, the predicted vector sum values were approximately double the measured values.

In the previous studies, Boshuizen *et al.* (1990) reported that the vector sum of vibrations of tractors on an asphalt road was in the range of 0·67–0·98 m s^{-2}, while on a brick road the values were between 1·76 and 2·03 m s^{-2}. Bovenzi and Betta (1994) reported a vector sum of 1·07 m s^{-2} on the farm profile while performing ploughing, mowing, fertilizer spreading at 2·9–5·9 km h^{-1} with 33·5–63·4 kW tractors. The vector sum of 1·22 m s^{-2} was obtained on tractors of 33·5–63·4 kW towing loaded trailers at 6 km h^{-1} on farm tracks and 0·86 m s^{-2} was obtained on asphalt road at full throttle (maximum engine speed). These values were lower as compared to measurements made in our study probably because tractor operated with implements, which tends to dampen the vibration levels. Also, the tractor sizes used in the present study were smaller than those in the study by Bovenzi and Betta (1994).

Griffin (1990) reported 3·0 m s^{-2} overall rms value at 12 km h^{-1} on ISO 5008 (1979) smooth track but without mentioning the tractor rating. This is close to the value obtained from the model in the present study (3·76, 3·65, 3·29 m s^{-2} for 14·9, 26·1 and 37·3 kW tractors, respectively, at 12 km h^{-1}).

5.1.3. *Comparison with prescribed limits*

The predicted rms acceleration values from the model were higher, more sensitive to velocity and tractor size (Table 1) as compared to measured values. The effect of velocity and tractor size was not very clear from the measured values (Table 2).

In the present study, the median hours of operation was 1000 pa, indicating more than 3·3 h tractor-driving by farmers on a daily basis. This shows that the exposure limit would be exceeded in most cases as described in Sections 4.1.1 and 4.2.1, where 2·5 h EL was exceeded on the 14·9 kW tractor and remained close to 2·5 h EL on the 26·1 and 37·3 kW tractors for both modelled and measured values.

In a comparison of the overall ISO-weighted rms acceleration with ISO 2631-1 (1997) in the present study, the predicted values from the model were 0·42–0·94 h for all tractor velocity combinations, whereas, for measured values this was 0·67–3·84 h for the upper limit of the health caution zone in most of the cases. This again shows that with reported tractor operational time, the upper limit of health caution zone would be exceeded in most tractor–terrain–velocity combinations.

Comparison with standards has been done in very few previous studies (Sorainen *et al.*, 1998; Gerke & Hoag, 1981; Futatsuka *et al.*, 1998). Futatsuka *et al.* (1998) reported rms accelerations of 0·89 and 0·426 m s^{-2} for tractors (16·4 and 33·5 kW) leading to 0·598 and 11·43 h as the upper limit of the health caution zone. These values were very different from the present study measured values of 1·58–4·57 m s^{-2} on farm terrain for all tractor–velocity combinations, which results in 0·29–2·40 h of safe operations. Possibly, different tracks and tractors with suspended cabin were responsible for this difference.

A comparison of the model and measured values indicates the utility of the model. If the PSD of the terrain is known, the rms accelerations can be predicted. In the present study, since the PSD of the terrains were not known, a random farm track prescribed in ISO 5008 (1979) was used as input for the model. The rms accelerations from this model were higher than the measured values. Since the values were higher the limit as per ISO 2631-1 (1985) is more likely to be crossed or the upper limit prescribed by ISO 2631-1 (1997) will be less as compared to those obtained from the measured values. Therefore, the model with ISO 5008 (1979) track PSD as input can be safely used to predict the severity of vibration with respect to ISO health limits for tractors.

5.2. *Effect of whole-body vibrations on spine*

Both predicted and measured values exceeded the health norms of ISO standards indicating the severity of whole-body vibrations to which tractor-driving farmers were exposed. This suggests detrimental effects on the health of tractor-driving farmers and a need for a health study.

Several confounding factors make it difficult to determine the relationship between back problems and whole-body vibrations. These include age, sitting for long periods, posture, twisting moments of back, lifting heavy loads, climatically poor working conditions, work loads and stress (Hulshof & Zanten, 1987). No study has been conducted so far which attempts to control all these factors. In the present study, both the study and the control groups were chosen in such a way that except for tractor-driving the differences between the two groups were minimized to the maximum extent. Both the study and control groups belong to the same sub-ethnic group, have similar marital status, live in similar socioeconomic and cultural context, and have similar dietary habits. Our statistical analysis also shows that the study group and the control group were almost the same in all aspects examined.

In the present study, tractor-driving farmers reported regular backache more often (56%) than non-tractor-driving farmers (32%). However, the objective clinical evaluation revealed no difference between the two groups except a higher prevalence of sensory symptoms (numbness) and absence of knee jerk among tractor-driving farmers (Table 4). There was no statistically significant difference among the three specialists *viz.* radiologist, neurosurgeon and orthopaedic surgeon in MRI scan evaluation.

The clinical and MRI similarities between tractor-driving farmers and non-tractor-driving farmers seem to suggest that activities of both groups did not produce significantly different measurable changes. Since both the study and control groups are similar, it is possible that rural farming life-style contributes more to degeneration than whole-body vibration alone.

It is possible that the cause of backache could lie in tissues and is caused by changes not demonstrable by MRI and clinical evaluation. Serousi and Pope (1987) hypothesized that muscle fatigue could be the result of vibration exposure. The possibility of vibration affecting tendon or muscle structure and/or pain receptors and the origin or evaluation of these changes need further evaluation.

6. Conclusions

Comparisons of measured as well as predicted root mean square (rms) accelerations with ISO 2631-1 (1985) indicate that severity of vibration as 8-h 'exposure limits' on all terrain–tractor combinations was exceeded. When evaluated according to the ISO (1997) standard for both measured and predicted values, 8-h working exceeded the upper limit of 'health guiding caution zone'. The ISO-weighted rms accelerations predicted from the mathematical model with ISO 5008 track were higher as compared to measured values on farm and non-farm terrains. Therefore, in the absence of experimental data, the model with ISO 5008 (1979) smooth track can be safely used to predict severity of vibrations for tractors with respect to existing ISO standards.

As indicated earlier, the medical study was motivated by the severity of vibrations at the seat level observed during experimental and mathematical model studies. The medical study showed that there was no objective difference between the tractor- and non-tractor-driving farmers as assessed by clinical evaluation and magnetic resonance imaging. There was, however, a statistically higher incidence of reported low back pain among tractor-driving farmers as compared to non-tractor-driving farmers. No specific objective cause could be attributed to the symptoms of backache as described by the tractor-driving farmers by either clinical or magnetic resonance imaging evaluation.

The difference between medical and measurement -model studies can be explained as follows. It is possible that the rural farming life-style, which includes occasional lifting of farm inputs and produce weighing up to 300 N during sowing and harvesting, contributes as much to diagnostically detectable degeneration as whole-body vibrations. As a result, non-tractor-driving farmers end up having similar degenerative changes as tractor-driving farmers. The only difference found between tractor-driving farmers and non-tractor-driving farmers is the operator's perception of pain and the present diagnostic methods are unable to provide a reason for this. For the health standards to be able to differentiate between health changes of tractor-driving farmers due to vibrations as compared with non-tractor-driving farmers they may need to include the operator's perception of pain besides detectable tissue degeneration until the evolution of more sensitive diagnostic methods.

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Appendix A: Tractor parameters

Parameters	*14·9 kW*	*26·1 kW*	*37·3 kW*
Body mass M_b, kg	1380	1580	2045
Axle mass M_a, kg	110	110	200
Front wheel mass M_1, M_2, kg	30	30	30
Rear wheel mass M_3, M_4, kg	80	80	100
Body roll inertia $I_{b\phi}$, kg	772	884	1145
Body pitch inertia $I_{b\theta}$, kg m^2	1581	1738	2250
Body yaw inertia $I_{b\psi}$, kg m^2	1581	1738	2250
Axle roll inertia $I_{a\phi}$, kg m^2	60	60	120
Axle yaw inertia $I_{a\psi}$, kg m^2	60	60	120
Front wheel spin inertia $I_{1\theta}$,$I_{2\theta}$, kg m^2	4	4	4
Rear wheel spin inertia $I_{3\theta}$,$I_{4\theta}$, kg m^2	42	42	42
Front axle pitch inertia $I_{a\theta}$, kg m^2	0	0	0
Front wheel roll inertia $I_{1\phi}$, $I_{2\phi}$, kg m^2	2	2	2
Front wheel yaw inertia $I_{1\psi}$,$I_{2\psi}$, kg m^2	2	2	2
Rear wheel roll inertia $I_{3\phi}$, $I_{4\phi}$, kg m^2	21	21	21
Rear wheel yaw inertia $I_{3\psi}$,$I4_{\psi}$, kg m^2	21	21	21
Front axle to body CG a, m	1·17	1·28	1·4
Rear axle to body CG b, m	0·63	0·74	0·84
Distance from rear axle to seat centre $b - l_x$, m	0·12	0·25	0·15
Longitudinal distance from CG to seat centre l_x, m	0·51	0·49	0·69
Wheel half-track, rear t_r, m	0·65	0·67	0·70
Wheel half-track, front t_f, m	0·65	0·67	0·70

Appendix A — (*Continued*)

Parameters	*14·9 kW*	*26·1 kW*	*37·3 kW*
Ground to body CG h_b, m	0·74	0·68	0·80
Distance from ground to seat $h_{b+}\ l_z$, m	1·21	1·12	1·27
Vertical distance from CG to seat l_z, m	0·47	0·44	0·47
Ground to axle CG h_a, m	0·41	0·41	0·46
Ground to front axle pivot h_p, m	0·47	0·47	0·50
Front tyre radius r_f, r_1, r_2, m	0·35	0·35	0·35
Rear tyre radius r_r, r_3, r_4, m	0·73	0·73	0·73
Tyre stiffness, longitudinal front k_{1X}, k_{2X}, kN m^{-1}	0	0	0
Tyre stiffness, longitudinal rear k_{3X}, k_{4X}, kN m^{-1}	700	700	700
Tyre stiffness, lateral front k_{1Y}, k_{2Y}, kN m^{-1}	140	140	140
Tyre stiffness, lateral rear k_{3Y}, k_{4Y}, kN m^{-1}	220	220	220
Tyre stiffness, vertical front k_{1Z}, k_{2Z}, kN m^{-1}	330	330	330
Tyre stiffness, vertical rear k_{3Z}, k_{4Z}, kN m^{-1}	400	400	400
Drive line stiffness, front k_1, k_2, kN m^{-1}	0	0	0
Drive line stiffness, rear k_3, k_4, MN m^{-1}	1·0	1·0	1·0
Tyre damping, longitudinal front c_{1X}, c_{2X}, kN s m^{-1}	0	0	0
Tyre damping, longitudinal rear c_{3X}, c_{4X}, kN s m^{-1}	4·0	4·0	4·0
Tyre damping, lateral front c_{1Y}, c_{2Y}, kN s m^{-1}	2·0	2·0	2·0
Tyre damping, lateral rear c_{3Y}, c_{4Y}, kN s m^{-1}	1·6	1·6	1·6
Tyre damping, vertical front c_{1Z}, c_{2Z}, kN s m^{-1}	4·5	4·5	4·5
Tyre damping, vertical rear c_{3Z}, c_{4Z}, kN s m^{-1}	5·0	5·0	5·0
Drive line damping, front c_1, c_2, kN sm rad^{-1}	0	0	0
Drive line damping, rear c_3, c_4, kN sm rad^{-1}	10	10	10

CG, centre of gravity

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