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ANALYSIS OF WHOLE-BODY VIBRATION LEVELS DURING SKIDDING

J.-M. Golsse and P.A. Hope

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PREFACE

To further the industry's understanding of the relationship between relatively high speed off-road travel and machine operator well-being, FERIC evaluated the motion-induced vibration levels generated by a sample of wheeled skidders working in a variety of operating conditions.

The reader is cautioned that the results presented are specific to the machines and conditions studied, and thus should not be applied elsewhere without due discretion. Moreover, since the study was neither designed nor focussed to highlight "good" or "poor" machines, the skidder brands and models have not been given.

For the sake of clarity and brevity, results of limited interest have been omitted from this report. Further details of the study may be obtained through direct communication with FERIC. All quantitative data are given in SI units; an imperial conversion table is appended for the reader's benefit.

The authors would like to thank the personnel of the following companies for their willing participation:

- Coopérative St. Dominique du Rosaire
- E.B. Eddy Forest Products Limited
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SUMMARY

High Whole-Body Vibration (WBV) levels on heavy off-road equipment have been linked to fatigue and potential health problems (Troup 1978; Pope and Frymoyer 1986), though little information relates directly to Canadian logging applications. Of the forest industry's machines, skidders likely pose the highest WBV hazard because of the prerequisite for relatively high-speed travel in rough terrain. Indeed, some earlier research has shown skidder WBV levels often exceed commonly accepted ISO standards, but FERIC felt that further study was warranted over a broader range of conditions to help define the existence/magnitude of the problem. A secondary objective was to increase industry understanding of vibration theory and issues.

To these ends, ride-induced vibration was measured for a sample of grapple and cable skidders, both with and without suspension seats, during actual operation in Ontario and Quebec. Subsequently, the operators' daily exposure levels were determined from these measurements and timing data.

Recorded acceleration levels for all machines were consistently higher than the acceptable limits given by the ISO 2631 Standard. While the vertical (z-axis) values were worse than those in the horizontal (x- & y-axes), none of them was satisfactory. On an equal exposure-time basis, grapple skidders were generally less detrimental than cable skidders with suspension seats which in turn were preferable to those without suspension seats. But, because of the larger travel time component in the work cycle which increases the daily exposure time, grapple skidder operators may be exposed to similar or even greater ride vibration effects than cable skidder operators. As a whole, skidder operators appear to be exposed to some of the most severe ride-induced vibrations encountered on industrial machines.

Reducing the WBV in skidders is not a simple task. Factors such as the nature of the job itself, the cost required to design and adapt adequate isolation systems to these machines, and remaining uncertainty about the consequences of intermittent vibration exposure all tend to hinder positive improvement.

As long as the industry does not request better designed cabs, it is doubtful that most manufacturers will take such an initiative. In the meantime, FERIC plans to evaluate the viability of some partial solutions to reduce WBV levels on skidders.

INTRODUCTION

Past studies have shown that heavy-machinery operators exposed to high WBV levels are prime candidates to experience fatigue, and also suffer certain kinds of physiological deterioration of the spinal system (Pope et al. 1980). Unfortunately, while WBV levels have been studied on many industrial machines around the world, little information relates directly to Canadian logging operations.

Of the machines common to logging operations, skidders probably pose the greatest WBV hazard because of the prerequisite for high-speed travel in rough terrain. As such, the intensity of WBV levels on skidders deserves attention, particularly since there are several thousand of such machines working across Canada. Wilson (1984) and Hope (1985), as well as other researchers, have investigated WBV levels on skidders in Canada and found them often to be higher than the commonly accepted limits. To complement this research, FERIC felt that further study was warranted over a broader range of conditions. Therefore, in 1985, FERIC measured WBV levels on a sample of skidders operating in typical eastern Canadian conditions. The objective was to define the magnitude of the problem and indicate the need for future research towards potential solutions. (This report summarizes the results of the study).

It is important to note that these results are specific to the machines and conditions as studied. They merely illustrate the potential WBV problem, and therefore should only be applied elsewhere with extreme caution.

General Vibration Principles

Vibration is essential to life. For example, we see, feel, hear, and communicate verbally through some form of vibrating mechanism. These vibrating forces emitted at specific frequencies are perceived or felt by us through different parts of our body which act as complex sensors capable of transmitting the input information electrically to our brain for identification and response.

While numerous vibrating inputs are pleasant, comfortable and often welcome sources of information necessary for our day to day living, their degree (amplitude) and distribution (frequency) over time will dictate the levels of pleasure and comfort we attach to them. For example, sound becomes noise once it has reached a level higher than that which we can accept.

Some vibrations to which humans are exposed stem from working with or on machines. Vibrating forces with high amplitude and low cycle frequency (i.e., < 1 Hz) such as those encountered on a boat in turbulent seas, or in a high cab on a slow moving vehicle, are called Motion Sickness Vibrations. Vibrating forces with higher frequency levels (i.e., > 80 Hz) affecting the upper body limbs, such as those transmitted by a chain saw's engine and chain motion, are called Hand-Arm Vibrations. Finally, vibrating forces with a frequency range between 1 and 80 Hz as sensed by the entire body, are known as Whole-Body Vibrations (WBV). Such vibrations are commonly associated with moving vehicles. For any vehicle, they are a function of the travel speed and the amount and nature of obstacles in the vehicle's path. These WBV levels represent the focus of this report.

Whole-Body Vibration typically results from two types of forces acting on the operator. A non-cyclical force transmitted over a very short time span, and for which the peak level is reached instantaneously is called a shock load. A skidder blade striking a stump or a sudden drop into a hole may produce these shock loads. If these shock loads are sufficiently great, the operator may be thrown from his seat or struck by objects flying around in the cab. Less sudden forces are created by the machine's regular motion over rough terrain. These are the most common motion-induced vibrating forces that an operator encounters during his daily work. The effects of such forces vary with the duration of exposure. Thus, they are more difficult to define and control than the instantaneous damage caused by high shock loads. Whole-Body Vibration considers these forces in combination and defines the effects of repetitive forces acting in a specific frequency range.

The frequency range of 1 to 80 Hz is significant in terms of the body's response. The human body is composed of a number of masses (limbs, head, internal organs, muscles, etc.) bonded by springs and dampers (tendons, ligaments, vertebral disks, etc.). This complex structure obeys a law of physics known as the resonance phenomenon. The resonant frequency for the body as a whole and for the abdomen lies in the 4 to 8 Hz range. The spine will be in resonance between 10 to 12 Hz and the lungs at about 50 Hz. When a mass is exposed to a vibrating force equivalent to its resonant frequency, it will start moving at the force's frequency while its displacement (amplitude) will often exceed that of the input force itself (Le Borgne, 1984). In a human body, this unwelcome situation may create chronic stresses and sometimes even permanent damage to the affected organs or body parts.

One of the principal body parts affected by these forces is the spinal structure. The most prevalent back disorders are commonly referred to as lower-back pain. Primary pain arises from the parts of the spine containing nerves (muscles, ligaments, spinal dura matter). It cannot originate in the disks or other parts without nerves (Troup, 1978). When a disk is damaged, the pain is felt through other spinal components exposed to higher-than-normal loads because of the damaged disk.

The complex inter-relationships between fatigue, lower-back pain and machine vibration are not fully understood, particularly since the issue is often clouded by external socio-economic factors. However, it has been determined that a relationship does exist (Pope et al. 1980). Faced with high WBV levels, machine operators react in several ways. Some take more frequent/longer breaks or limit machine speed to their comfort level at the expense of productivity. Others choose to risk fatigue, again at the cost of productivity, or risk lower-back discomfort. Either way, the cost to industry is considerable.

By way of example, beyond the lost production, back injuries account for about one-third of all workers compensation claims in Canada. The Ontario WCB spent about $400 million for back-related claims alone in 1984 (Imrie, 1986). Naturally, just a fraction of this total is likely related to vibration exposure, but the figures do illustrate the potential severity of the problem. It therefore is of prime importance to determine the scope of Whole-Body Vibration within the forest industry's operations.

DEFINITIONS

It may be useful to define a few terms which are specific to vibration analysis and could be misleading.

Whole-Body Vibration describes the effects of mechanical vibrations on the human body. In this case, it is the effect of the skidder's motion over rough terrain on the operator's well-being. In an attempt to consolidate the large number of parameters involved in WBV measurement (i.e., mechanical, biological and psychological), the International Standards Organization developed a standard (ISO 2631) in 1974 for defining, measuring and analysing WBV. The 1978 second edition of this Standard is used in this report. Because of the roughness and intermittent nature of the ride, the ISO Standard may not be truly applicable to skidders. It nevertheless has been followed for lack of a better standard, but should be considered as a guide only.

WBV is measured in three orthogonal directions (Figure 1), such that the x-axis is in the direction of travel, the y-axis is tranverse to it, and the z-axis is in the vertical direction passing from the seat to the head of the operator.

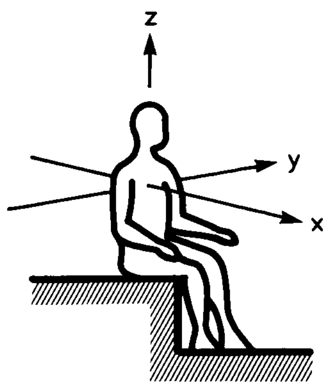

Figure 1. Direction of coordinate system for mechanical vibrations influencing humans (from: ISO 2631, 1978).

The ISO Standard defines three vibration-level limits, based on acceleration levels:

1- Exposure Limit (EL)
This is the limit above which health or safety may not be preserved.

2- Fatigue-Decreased Proficiency (F-DP)
This is the limit above which working efficiency may be impaired. It is also the limit for which time-dependent effects are assumed to create fatigue and reduced performance. The F-DP limit curve has the same shape as the EL limit but is half the magnitude (see Appendix A). F-DP typically applies to driving tasks.

3- Reduced Comfort Boundary (RCB)
This is the limit above which ride comfort may not be possible. The RCB level lies one-third below the F-DP level, and again has the same shape. It usually applies to the comfort of passengers.

The RCB is reached first, the F-DP second and the EL last under similar vibration-level inputs. The F-DP limit was used for this study since it refers to working efficiency.

For WBV, as for all other types of vibrations, not only the amplitude level of a particular force is important, but also the frequency range at which it occurs. By the ISO Standard, WBV are restricted to the 1 to 80 Hz range, and are measured in one-third octave frequency bands.

Weighting factors, given to each axis for every 1/3-octave band, are used to weight the frequencies in proportion to their significance to the body's resonant frequencies. In the z-axis, the 4-8 Hz range carries the most weight, while the 1-2 Hz frequencies are critical in the x- & y-axes. For a seated subject exposed to vertical (z-axis) vibrating forces, the body, while acting as a unit mass below 2 Hz, reaches its first resonance frequency between 4 and 6 Hz. However, above 10 Hz, the vibration displacement amplitude of the body becomes smaller than that of the exciting forces. In the case of thrust forces acting perpendicular (x and y-axes) to the line of action of the force of gravity on the seated human body, all critical resonant frequencies are limited to a 1 to 3 Hz range (Von Gierke and Goldman 1976). Thus different weighting factors are used for different frequencies in different lines of action. A table of weighting factors is provided in Appendix B.

Acceleration levels in metres per second squared (m/s^2) are usually expressed as <u>Root-Mean Squared</u> (RMS) values (Figure 2). This provides for a number representing an average acceleration integrated over a certain time period.

<u>Maximum Peak Acceleration</u> levels provide information on shock loads which would otherwise be lost in the RMS acceleration levels. This is particularly significant with skidders which often encounter major obstacles in their pathways (e.g., high stumps, rocks, and large holes).

<u>Crest Factors</u> (CF) help to define the roughness of a particular ride. They are the ratio of the weighted Peak acceleration level to its corresponding weighted RMS value.

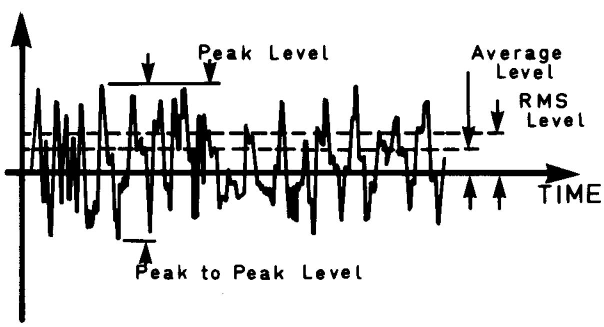

Figure 2. Relationship between RMS and Peak levels (from: Brüel & Kjaer booklet).

For more detailed information on this rather complex subject, the reader is advised to refer to the ISO Standard, as well as to related vibration analysis literature. A list of selected readings of potential interest is included at the end of this report.

INSTRUMENTATION

A Brüel & Kjaer (B & K) tri-axial piezoelectric accelerometer (model 4321), mounted in a "home-made" seat pad captured raw vibration data on the machine's seat (Figure 3-a). A single-axis B & K 4371 accelerometer was used concurrently to sense the vertical vibrations on the machine floor under the seat. Their outputs were recorded in the field on a B & K 7007, four-channel, FM tape recorder (Figure 3-b) equipped with four ZM 0060 vibration units (Figure 3-c).

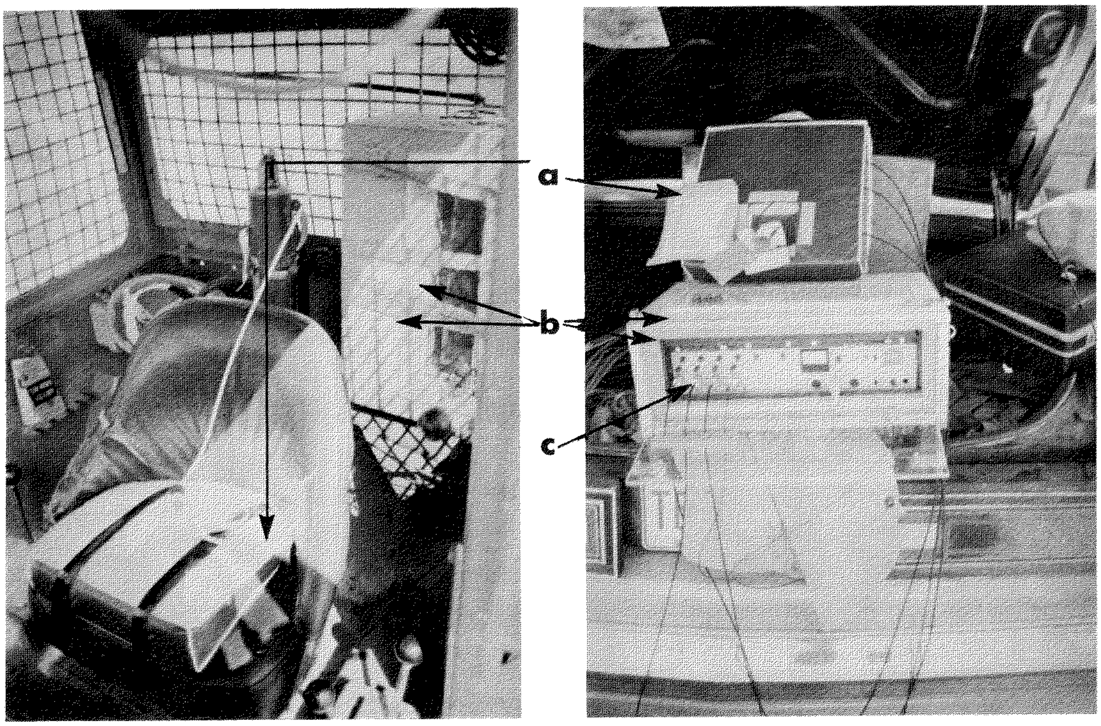

Figure 3. Recording instrumentation.
a) B & K 4321 tri-axial accelerometer & seat pad.
b) B & K 7007 FM tape recorder in protective box.
c) B & K 0060 vibration units in tape recorder.

Recorded data were analysed in-house with a B & K 2131 Digital Frequency Analyser for determination of RMS non-weighted values over the full frequency range. Results were plotted on a B & K 2308 plotter. Safe exposure times as allowed by ISO 2631 were determined from this analysis.

Further analysis to obtain weighted Peak and RMS acceleration levels (1-80 Hz) was conducted with the help and instrumentation of the Institut de recherche en santé et en sécurité du travail du Québec (IRSST) in Montreal. Subsequently, Crest Factors were determined from these data. The weighting network used was that of a B & K 2512 Human Response Vibration Meter. It acted as an interface between the tape recorder and a B & K 2636 Measuring Amplifier for weighted Peak determination. In parallel to it, a modified B & K 2218 Precision Integrating Sound Level Meter was used for weighted RMS outputs.

STUDY CONDITIONS

From June to August 1985, FERIC personnel collected data at five different locations in Quebec and Ontario. All machines were tested during regular skidding cycles and driven by experienced company operators.

Machine Sample

The machine sample consisted of eight wheeled skidders, tested in ten configurations. Two of the eight machines were re-tested with a polymer cushion on the machine seat. The ten test configurations were separated into the three major groups shown in Table 1:

Group 1 represented the two grapple skidders.
Group 2 represented the three cable skidders without suspension seats.
Group 3 represented the five cable skidders with suspension seats.

Though limited, the sample is fairly representative of the diversity of machines, tires and ages typical to eastern Canadian skidding operations.

Table 1. Machine characteristics

Group	Machine*	Skidder type	Seat type	Power (kW)	Tires**	Transmission	Year
1	1	Grapple	No Susp.	116	71 × 24.5 - 32	3 speed	1985
	2	Grapple	Susp.	90	71 × 24.5 - 32	8 speed	1985
2	3	Cable	No Susp.	67	65 × 18.4 - 34	3 speed	1981
	4	Cable	No Susp.	99	65 × 18.4 - 34	3 speed	1985
	4-a	Cable	No Susp.	99	65 × 18.4 - 34	3 speed	1985
3	5	Cable	Susp.	89	68 × 18.4 - 34	3 speed	1985
	6	Cable	Susp.	90	74 × 30.5 - 32	8 speed	1980
	7	Cable	Susp.	67	66 × 50 - 26	8 speed	1982
	8	Cable	Susp.	99	65 × 18.4 - 34	3 speed	1985
	8-a	Cable	Susp.	99	65 × 18.4 - 34	3 speed	1985

Note: * Machines 4-a & 8-a were equipped with an extra seat pad.

** In North America, tire sizing is normally in imperial units. A 65 × 18.4 - 34 tire would therefore be 65" in diameter, 18.4" wide and would have a 34" bead diameter.

Environmental and Operational Factors

Details of the diverse environmental and operational factors encountered are provided in Table 2. Excellent summer conditions occurred in all cases; there was no precipitation during the study. Skidding represented an equal mix of full-trees and tree lengths.

Table 2. Environmental and operational factors

Machine	Location	Harvesting system *	Average number of trees per load	soil type **	Terrain classification	Average travel distance loaded (m)	Average travel speeds off-Road EMPTY (m/min)	EMPTY (km/h)	LOADED (m/min)	LOADED (km/h)
1	A	FT	8	-	3.1.1.	125	78.7	4.7	59.5	3.6
2	A	FT	12	S	1.3.1.	97	101.3	6.1	90.3	5.4
						$\bar{x}$= 111	90.0	5.4	74.9	4.5
3	B	TL	14	S/C	2.3.1.	101	64.9	3.9	65.4	3.9
4	C	TL	35	S/L	1.1.1.	133	102.2	6.1	113.7	6.8
4-a	C	TL	32	S/L	1.1.1	89	107.6	6.5	107.6	6.5
						$\bar{x}$= 108	91.7	5.5	95.7	5.7
5	D	FT	12	L	3.2.1.	75	65.8	3.9	31.3	1.9
6	E	FT	25	C	3.1.1.	490	106.8	6.4	81.2	4.9
7	E	FT	22	C	3.1.1.	350	86.1	5.2	62.7	3.8
8	C	TL	32	S/L	1.1.1.	114	131.9	7.9	96.2	5.8
8-a	C	TL	26	S/L	1.1.1.	153	110.4	6.6	97.0	5.8
						$\bar{x}$= 214	100.2	6.0	73.7	4.4
					$\bar{x}$	173	95.6	5.7	80.5	4.8

Note: * FT = Full-tree, TL = Tree length
** S = Sand, L = Loam, C = Clay

Soil types varied from sand to clay, with some sandy loams. Soil moisture conditions ranged from dry to wet. Ground roughness was similar in each case for the travel empty and travel loaded trails. Terrain classification follows Mellgren, 1980.

Travel distance loaded averaged 173 m. Travel speed averaged 95.6 m/min (5.7 km/h) empty, and 80.5 m/min (4.8 km/h) loaded.

Operators

General background information on the seven operators is given in Table 3. The comparison of the operators' anthropometric dimensions (height and weight) to the national statistics (Demjirjian, 1980) indicates that the sample is consistent with the overall Canadian adult male population (i.e., ranging from the 10th to 90th percentile, but mostly around the 50th percentile).

Their skidding experience ranged from 0.7 to 16 years ($\bar{x}$ = 6.9 years). Experience may affect operating efficiency, smoothness of ride, and general driving care. Thus, while the sample is probably representative of the general skidder operator population, it does raise some concerns about the comparability of the data. The variations in machines and operating conditions also suggest that the results be regarded only as indicators of relative performance. As such, the data are intended to provide an overview of the WBV problem in a variety of skidding situations.

Table 3. Operator characteristics

Machine	Age (yrs)	Experience (yrs)	Height (cm)	Weight (kg)
1	24	4	166	59
2	44	16	170	77
3	26	7	166	77
4*	28	8	173	73
5	19	0.7	175	70
6	32	3	183	93
7	31	10+	170	82
8*	28	8	173	73

* Same operator

RESULTS AND DISCUSSION

Timing

Since WBV analysis deals with the effect of motion-induced vibration on human beings, the data are only pertinent for the cycle components during which the operator is in the machine in motion. These are:

Travel Empty (TE)
Travel Loaded (TL)
Piling (PI)

Terminal times (loading, unloading, delays) are not taken into account since the operator is out of the cab, for cable skidders; or the machine is not in motion, for the grapple skidders.

During the study period, detailed timing of the cycle elements was conducted for about 9 hours in conjunction with WBV recording. Table 4 summarizes the relative cycle time distribution for the three machine groups. Maneuver (MA) and Move During Loading (MDL) are short duration components occuring after and/or during TE and TL; they therefore have been included with them for analysis purposes.

Table 4. Cycle time distribution per skidder group

Skidder group	Time distribution (%)									
	Time in-motion								Terminal time	Total
	te	MA	TE*	tl	MDL	TL*	PI	Total		
Grapple	25	7	32	33	4	37	3.5	72.5	27.5	100
Cable without Susp.	8	3	11	8	5	13	8	32	68	100
Cable with Susp.	15	5	20	20	3	23	4	47	53	100

Note: * TE = te + MA; TL = tl + MDL

Because of their mode of operation, grapple skidders spend proportionally more time in motion than cable skidders. The difference in cycle time distribution for the two cable skidder groups appears directly attributable to the disparity in average skid distance (108 vs 214 m).

Weighted RMS and Peak Acceleration Levels, Overall Sample

Tables 5 and 6 present the weighted RMS and Peak acceleration levels respectively for the entire sample. Figure 4 combines the data graphically. In both cases (RMS & Peak), the data suggest that vibration levels in each axis are highest during the TE phase of the cycle, followed by TL and PI respectively. This probably reflects the higher average travel speed during TE, and the stabilizing effect of the load during TL. Moreover, it is apparent that vibration in the z-axis (vertical) dominates that in both the x- and y-axes.

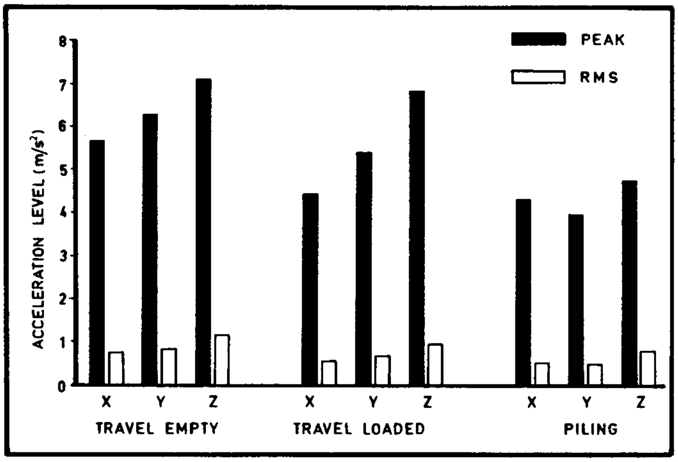

Figure 4. Weighted RMS and Peak acceleration levels per activity, overall sample.

Table 5. Weighted RMS acceleration levels, overall sample

Statistical parameter		TE (n* = 22)			TL (n = 17)			PI (n = 8)		
		X	Y	Z	X	Y	Z	X	Y	Z
Acceleration level m/s²	Mean	0.75	0.82	1.15	0.54	0.67	0.95	0.54	0.49	0.80
	S.D.**	0.21	0.29	0.43	0.22	0.31	0.43	0.33	0.27	0.62
	Range	0.43-0.98	0.46-1.43	0.47-1.77	0.30-0.96	0.33-1.29	0.39-1.66	0.08-1.17	0.24-1.06	0.31-2.19

* n = Sample size ** S.D. = Standard Deviation

Table 6. Weighted Peak acceleration levels, overall sample

Statistical parameter		TE (n* = 22)			TL (n = 17)			PI (n = 8)		
		X	Y	Z	X	Y	Z	X	Y	Z
Acceleration level m/s²	Mean	5.66	6.27	7.08	4.41	5.38	6.80	4.28	3.93	4.74
	S.D.**	1.97	1.98	3.48	2.08	2.11	2.74	2.67	1.70	2.44
	Range	3.25-8.00	4.12-8.14	2.24-14.83	2.37-8.42	2.37-9.76	2.37-11.66	1.26-10.00	2.24-6.70	2.24-8.41

* n = Sample Size ** S.D. = Standard Deviation

<u>Weighted RMS and Peak Acceleration Levels per Skidder Group</u>

Figure 5 graphically presents the weighted RMS acceleration levels per activity separately for each machine group. The numeric data are appended in Appendix C for reference.

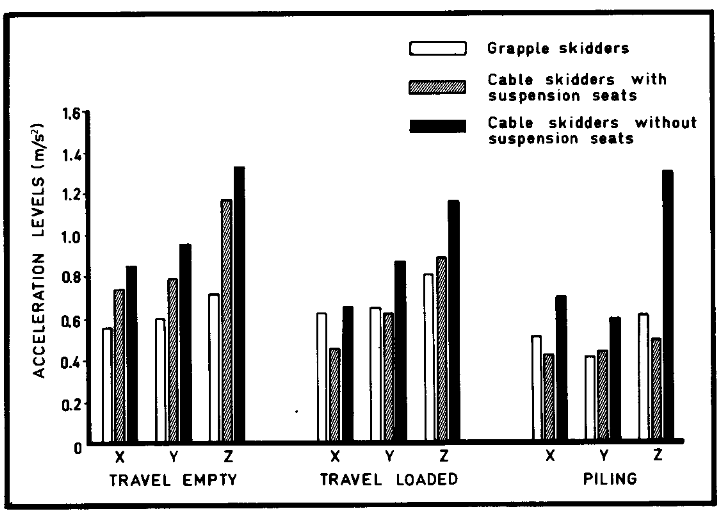

Figure 5. Weighted RMS acceleration levels per activity per skidder group.

While the variability of the study machines and conditions restricts direct comparison, some general trends are suggested. In every case (axis and activity), the cable skidders without suspension seats provided the roughest ride (i.e., highest acceleration levels). The grapple skidders appear to offer some advantage over cable skidders with suspension seats during TE, possibly because of differences in machine weight distribution, but there is little difference during the other motion related activities. As for the overall sample, vibration in the z-axis dominates that in the x- and y-axes for each machine group.

Figure 6 graphically compares the relative vibration per skidder group based on Peak acceleration levels.

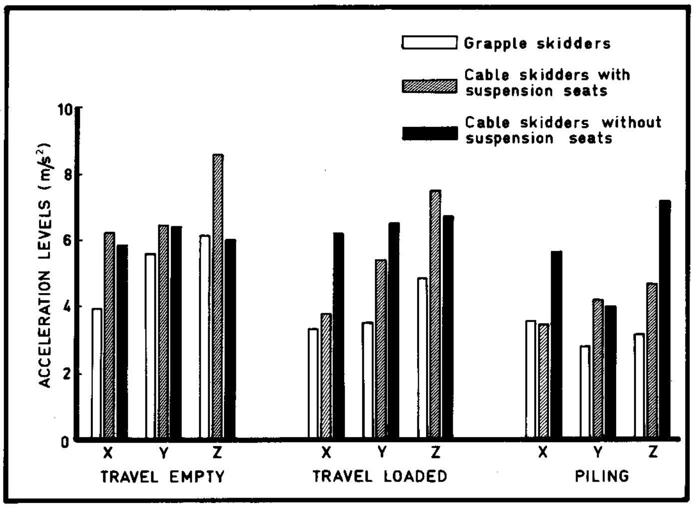

Figure 6. Weighted Peak acceleration levels per activity per skidder group.

Again, grapple skidders tended to provide the smoothest ride, followed respectively by cable skidders with and without suspension seats with one notable exception. During TE, Peak vibration levels for the suspension seats were actually higher than those for non-suspension seats. This apparent contradiction to common belief and the earlier trends might be explained by two factors.

The first is related to an inherent characteristic associated with basic suspension seats. In general, though effective at higher frequency, such seats are not capable of reducing the critical low-frequency accelerations (1 to 3 Hz) and may often even amplify them (Kyeong et al. 1985). This explains why there is presently considerable ongoing research into active and semi-active suspension seats, as opposed to traditional spring-mounted units.

Secondly, the test sample of suspension seat skidders comprised a number of situations which may have led to unduly low RMS acceleration levels (see Tables 1 and 2). Of the four machines sampled (5, 6, 7, 8), machine 5 was driven at comparatively low speed; machine 6 travelled along a deeply-rutted track with its belly-pan essentially sliding over a smooth surface (Figure 7); and machine 7 was equipped with wide tires which are believed to absorb shocks and reduce angular roll under similar speeds and conditions, though this could not be confirmed because of the nature of the study. As such, the much-believed benefits of traditional suspension seats remain in doubt.

Figure 7. Machine No. 6 skid trail, belly-pan sliding over a smooth surface.

Effects of Seat Configuration

A comparison of vibration levels during travel on machines 4 & 8 may shed further light on the suspension seat question. These two machines were identical models (only the seat differed) driven by the same operator on the same site. Thus, the comparison is more controlled. As shown in Table 7, RMS acceleration levels with the suspension seat were, in all cases, comparable or <u>higher</u> than with the non-suspension seat. While not conclusive, this suggests that the supposed vibration damping characteristic of suspension seats may not hold true in off-road situations. This matter requires further research in more controlled conditions.

In addition, the same two machines were re-tested after inclusion of a prototype polymer seat pad manufactured by Spenco Medical Corporation. The results from this experiment proved inconclusive, though it appeared that the pad may provide some benefit in reducing higher frequency vibration. This topic also requires further investigation.

Table 7. Seat configuration effect (RMS levels)

Axis	Cycle Component	Non-Suspension seat Machine 4	Suspension seat Machine 8
		Mean ± S.D.	Mean ± S.D.
X	TE	0.67 ± 0.13	0.90 ± 0.16
	TL	0.47 ± 0.13	0.48 ± 0.21
Y	TE	0.71 ± 0.03	0.61 ± 0.83
	TL	0.64 ± 0.32	0.21 ± 0.75
Z	TE	1.29 ± 0.18	1.23 ± 0.32
	TL	0.84 ± 0.74	1.00 ± 0.65

Crest Factors

Crest Factors (CF) are the ratio between the weighted Peak and the weighted RMS acceleration levels. They are used to define the roughness of a particular ride by highlighting the degree that Peak values deviate from the norm. Table 8 presents Crest Factors per machine group during travel loaded. Crest Factors were highest for those machines with suspension seats, again possibly as a result of the factors mentioned previously (low RMS, high Peaks). However, the ISO Standard states that if CF's exceed the value of 3, the limits should be regarded as "very tentative". In all cases, the CF's measured exceeded this limit which suggests that the vibration levels are extremely severe, exactly how severe however is uncertain.

Table 8. Crest Factors as a function of skidder group, (TL)

Skidder group	Axis		
	X	Y	Z
Grapple	6.35	7.46	7.18
Cable without susp.	7.73	6.95	5.05
Cable with susp.	8.33	8.79	7.43

Maximum Allowed Exposure Times

Table 9 compares the operators' actual vibration exposure time to the maximum allowed as defined by the ISO 2631 F-DP (fatigue-decreased proficiency) limits. Such maximum exposure times are based respectively on the most critical frequency over the 1.6 to 8.0 Hz range for the RMS acceleration levels recorded during the study. Shift length has been standardized to 8 hours (85% utilization) to conform to ISO 2631 and to allow for meaningful comparison. Actual exposure times per activity are based on the cycle-time distributions as observed. However, the cycle-time distribution for the two cable skidder groups has been averaged since the variation was solely related to differences in skid distance.

Table 9. Actual and allowed times per activity (RMS levels, ISO 2631, F-DP limits)

Skidder group	Activity	Actual time		Allowed time (hr) ISO, F-DP limits		
		% Recorded	Shift equivalent (hr)*	Axis X	Axis Y	Axis Z
Grapple	TE TL PI**	32.0 37.0 3.5	2.2 2.5 0.2	3.3 2.3 -	3.3 3.3 -	1.5 3.3 -
	Terminal time	27.5	1.9			
	Total	100	6.8			
Cable without Susp.	TE TL PI	15.5 18.5 6.0	1.1 1.2 0.4	1.0 2.0 2.5	1.5 1.5 3.5	0.8 1.0 2.5
	Terminal time	60.5	4.1			
	Total	100	6.8			
Cable with Susp.	TE TL PI	15.5 18.0 6.0	1.1 1.2 0.4	1.9 4.2 3.3	1.9 4.1 4.0	1.5 3.0 3.3
	Terminal time	60.5	4.1			
	Total	100	6.8			

Note: * Assumed shift length of 8 hrs, and 85% utilization.
** Too brief a sample to analyse (Group 1 only).

The degree of exposure percentages in Table 10 are derived from the data in Table 9 as the ratio of actual time to allowed time of exposure. The results suggest that cable skidders with suspension seats provide the least detrimental ride, but this conclusion is potentially in doubt because of the earlier arguments. Interestingly, the relatively low RMS levels observed with grapple skidders are negated by the greater proportion of time spent in motion (72.5% vs 39.5% for cable skidders).

Table 10. Percent of allowed times per activity as a function of the ISO F-DP limits (RMS levels)

Skidder Group	Activity	Percent of allowed*		
		X	Y	Z
Grapple	TE	67	67	147
	TL	109	76	76
	PI**	-	-	-
	Total (%)	176	133	223
Cable without Susp.	TE	110	73	138
	TL	60	80	120
	PI	16	11	16
	Total (%)	186	164	274
Cable with Susp.	TE	58	58	73
	TL	29	29	40
	PI	12	10	12
	Total (%)	99	97	125

* Calculated as actual time divided by allowed time (Table 9)
** Too brief a sample to analyse (group 1 only)

However, because of the variability in study conditions, any in-depth comparison between machine groups would be speculative at best. Such analysis might overshadow the fact that none of the three machine groups had overall acceptable vibration levels. Vibration saturation was frequently obtained during one time element alone. Moreover, where travel components were acceptable on their own, once combined, the levels approached or greatly exceeded the maximum allowable F-DP exposure limits in each axis. Again, the z-axis was dominant in vibration over-exposure, but none was acceptable.

CONCLUSIONS

The study's direct goal was to define the magnitude of Whole-Body Vibration during actual skidding activities. A selection of logging systems, operating sites, and machines types were investigated to represent fairly the range of conditions encountered on eastern Canadian operations. However, it should be noted that all vibration measurement was conducted during the summer, as the probable "worst-case" condition. It may be speculated that the WBV levels would be lower in winter because of the snow blanket, though this topic requires further research. A secondary objective of the report is to increase industry understanding of the WBV issue.

Recorded RMS acceleration levels were consistently higher than the acceptable limits given by the ISO 2631 Standard regardless of operating conditions, skidder configuration and seat type. Though the z-axis values generally dominated the x- and y-axes levels, none of them was satisfactory. Furthermore, the observed Crest Factors indicate that random impact loadings to the human body are greater than the maximum CF limits given by ISO. This would indicate that skidder operators are exposed to some of the highest WBV environments found in heavy-machinery operations. The only saving grace may be that the operators are only exposed to these high vibration levels for short duration periods. However, these periods accumulate to 40 to 70% of the daily working time.

The influence of this intermittent time factor on the overall exposure dose is not yet fully understood, and the scientific world has not been able to reach an agreement on its effects. However, it is the ISO's and the authors' opinion that a cumulative effect may exist. Thus, it appears wise to assume that fatigue, and maybe some potential health hazard, could result from these high exposure level accumulations.

For both social and economic reasons (e.g., high turn-over rate, lower worker productivity, high compensation costs), means to reduce these levels of acceleration should be investigated. Since some factors, such as the type of seat and the addition of a seat pad, appear to affect vibration levels, there may be hope that interim improvements could be implemented until the machine manufacturers manage to solve the complex problem of redesigning the machine cabs to lower WBV levels. Such potential improvements are to be the focus of FERIC's future research in the area of WBV. However, they reflect a partial solution at best.

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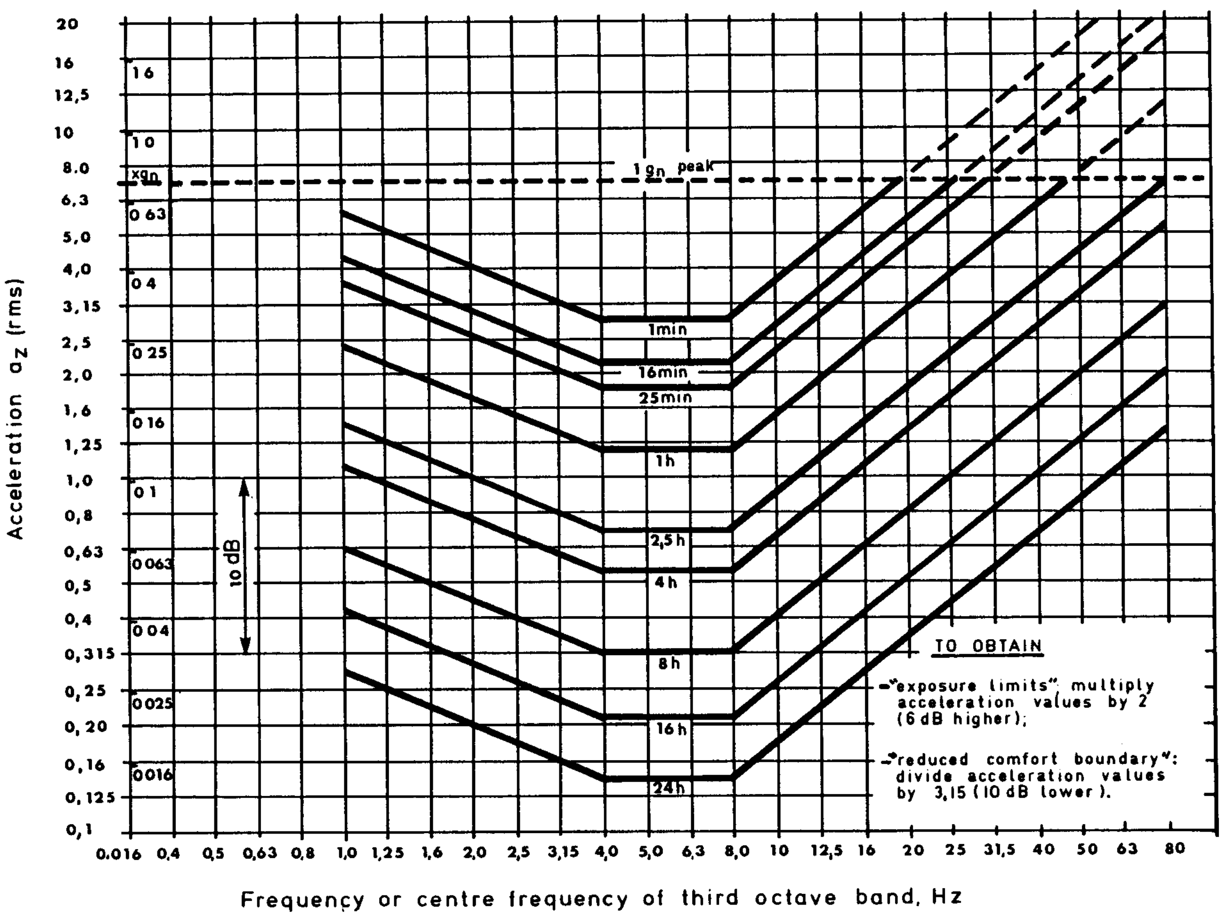
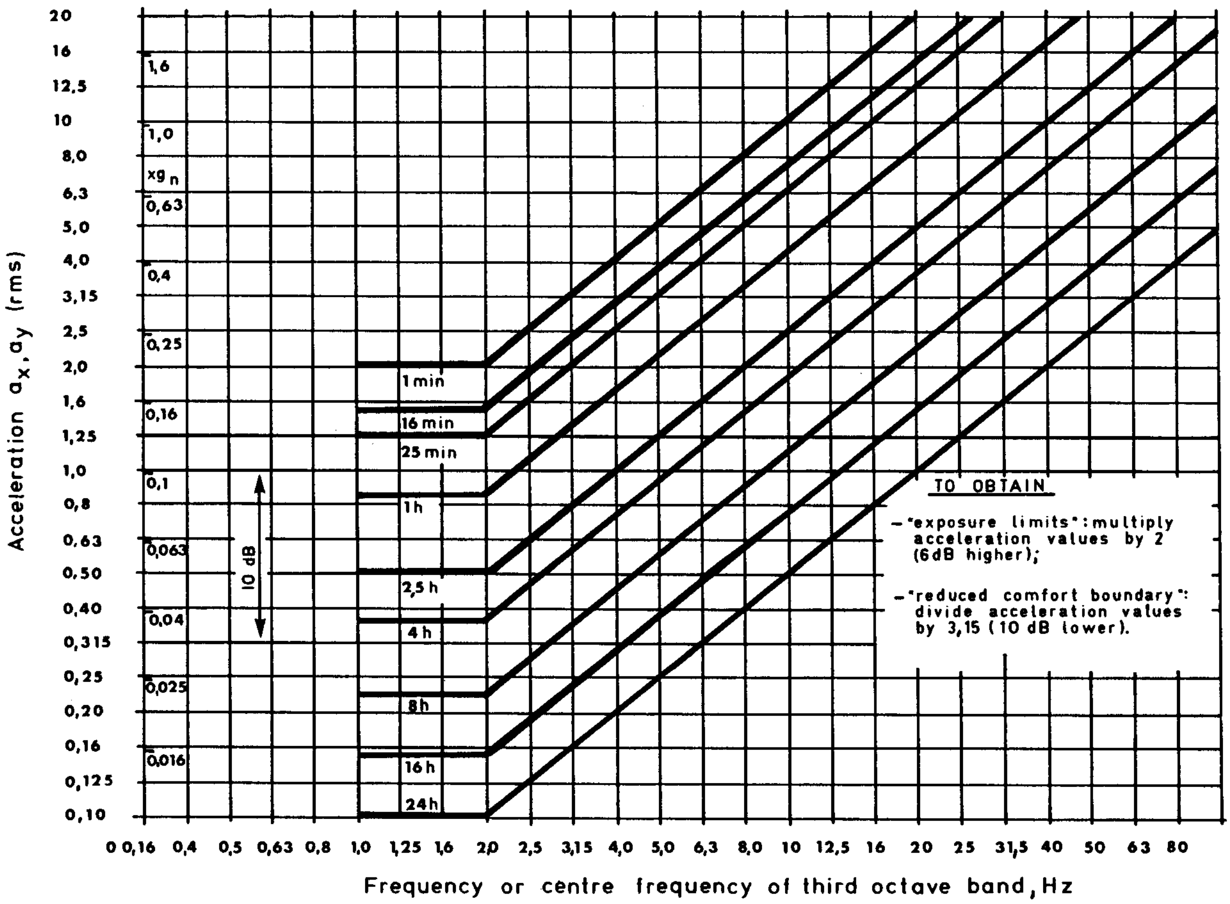
APPENDIX A1
FATIGUE-DECREASED PROFICIENCY LIMITS AS DEFINED BY ISO 2631

Vertical Direction (z-axis)



APPENDIX A2

Transverse Directions (x & y-axes)



APPENDIX B
WEIGHTING FACTORS (*)

Weighting factors relative to the frequency range of maximum acceleration sensitivity[1]

Frequency (centre frequency of third-octave band) Hz	Weighting factor for longitudinal vibrations (z)	Weighting factor for tranverse vibrations (x & y)
1.0	0.50 = - 6dB	1.00 = 0dB
1.25	0.56 = - 5dB	1.00 = 0dB
1.6	0.63 = - 4dB	1.00 = 0dB
2.0	0.71 = - 3dB	1.00 = 0dB
2.5	0.80 = - 2dB	0.80 = - 2dB
3.15	0.90 = - 1dB	0.63 = - 4dB
4.0	1.00 = 0dB	0.50 = - 6dB
5.0	1.00 = 0dB	0.40 = - 8dB
6.3	1.00 = 0dB	0.315 = -10dB
8.0	1.00 = 0dB	0.25 = -12dB
10.0	0.80 = - 2dB	0.20 = -14dB
12.5	0.63 = - 4dB	0.16 = -16dB
16.0	0.50 = - 6dB	0.125 = -18dB
20.0	0.40 = - 8dB	0.10 = -20dB
25.0	0.315 = -10dB	0.08 = -22dB
31.5	0.25 = -12dB	0.063 = -24dB
40.0	0.20 = -14dB	0.050 = -26dB
50.0	0.16 = -16dB	0.040 = -28dB
63.0	0.125 = -18dB	0.0315 = -30dB
80.0	0.10 = -20dB	0.025 = -32dB

1) 4 to 8 Hz in the case of $\pm a_z$ vibration
1 to 2 Hz in the case of $\pm a_x$ or $\pm a_y$ vibration.

(*) From ISO 2631 2nd ed. 1978.

APPENDIX C
WEIGHTED RMS ACCELERATION LEVELS PER MACHINE GROUP

Machine group	Statistical parameter		TE X	TE Y	TE Z	TL X	TL Y	TL Z	PI X	PI Y	PI Z
1	n*		4	4	4	3	3	3	1	1	1
Grapple skidders	Acceleration level m/s²	Mean	0.56	0.60	0.72	0.62	0.65	0.81	0.51	0.41	0.61
		S.D.**	0.12	0.09	0.18	0.05	0.11	0.05	-	-	-
		Range	0.45-0.64	0.50-0.70	0.55-0.93	0.61-0.68	0.58-0.78	0.78-0.86	-	-	-
2	n		9	9	9	5	5	5	3	3	3
Cable skidders without susp. seats	Acceleration level m/s²	Mean	0.85	0.96	1.32	0.65	0.87	1.16	0.70	0.59	1.30
		S.D.	0.17	0.36	0.42	0.35	0.48	0.64	0.56	0.42	0.85
		Range	0.54-1.14	0.68-1.53	0.76-2.11	0.38-1.24	0.41-1.60	0.32-2.02	0.08-1.17	0.24-1.06	0.50-2.19
3	n		9	9	9	9	9	9	4	4	4
Cable skidders with susp. seats	Acceleration level m/s²	Mean	0.74	0.79	1.17	0.45	0.62	0.89	0.42	0.43	0.49
		S.D.	0.24	0.21	0.41	0.12	0.25	0.35	0.07	0.18	0.18
		Range	0.42-1.08	0.33-1.09	0.47-1.68	0.30-0.67	0.33-0.87	0.32-1.46	0.35-0.51	0.24-0.64	0.31-0.73

* n = Sample size
** S.D. = Standard Deviation

APPENDIX D
CONVERSION TABLE

1 centimetre (cm)	=	0.39 inch
1 metre (m)	=	3.28 feet
1 kilogram (kg)	=	2.20 pounds (mass)
1 kilowatt (kW)	=	1.34 horse power

$1\ g = 9.81\ m/s^2 = 386\ in/s^2 = 32\ ft/s^2$