Seat selection guidelines to reduce whole-body vibration exposure levels in the SA mining industry

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Synopsis

This article deals with an investigation into the specification and use of appropriate seating systems to reduce whole-body vibration (WBV) exposure in typical vehicles used in the SA mining industry. The EU Directive EU/44/2002 to be legislated in 2005 in European countries, provides legal and economic motivation for this project. The criteria for seat selection can be condensed to the requirements in the directive, which mandates an action level of 0.5 m/s^2 and a vibration exposure limit of 1.15 m/s^2 for an equivalent 8-hour daily exposure period. As part of this study six suspension seats, which the manufacturers claim satisfy the requirements in ISO 7096[6], were tested to determine the most suitable seat for an articulated dump truck. Six test subjects, three 'light' and three 'heavy' as specified in ISO 7096[6], were used to estimate the seat transmissibility functions in the vertical direction of the six different suspension seats. Transmissibility functions were measured in the laboratory with two excitation levels of 1 m/s^2 and 2 m/s^2 r.m.s. in the 0.5–30 Hz frequency range, as well as one spectrum approximating the EM5 spectral class. SEAT values were calculated for road vibration data measured on a typical articulated dump truck. A set of seat selection guidelines that can be followed by vehicle manufacturers and suppliers, procurement officers and and the technical staff on a mine is proposed in this article. It is recommended that additional studies of the use and operating conditions of seating systems in the SA industry, as well as an epidemiological survey be commissioned to gather additional information on this subject.

Nomenclature

ADT	Articulated dump truck
DSTF	Dynamic seat testing facility
EM1	Frequency spectra associated with earthmoving equipment ('articulated or rigid frame dumper') according to ISO 7096
EU	European Union
ISO	International Standards Organisation
PSD	Power spectral density
r.m.s.	Root mean square
SEAT	Seat effective amplitude transmissibility
WBV	Whole-body vibration

Introduction

The short-term and long-term consequences of whole-body vibration (WBV) have been shown to adversely affect occupational health and safety. Some of these effects can lead to permanent disabilities, especially to musco-skeletal, spinal and gastro-intestinal disorders (Boshuizen and Hulshof[1]). One of the most common complaints from personnel exposed to high levels of WBV is that of lower back pain, an ailment difficult to diagnose. Otherwise, reduced ride comfort can lead to fatigue and reduced alertness of drivers and operators and ultimately to safety risks when they make poor decisions or fail to react proactively when hazardous situations develop.

The levels of WBV transmitted to drivers and operators of vehicles and other equipment in the South African mining industry have been associated with high risks that may pose health and safety threats. The South African mining industry has in the past paid little attention to WBV (Van Niekerk *et al.*[2]) although drivers of, in particular, earthmoving equipment are exposed to substantial levels of vibration. One obstacle the SA mining industry faces is the difficulty of establishing appropriate holistic assessment procedures and control measures to reduce the exposure of workers to WBV as well as a lack of knowledge to implement appropriate preventative measures.

In an effort to control whole-body vibration in industry, the European Union has issued the EU Directive 2002/44/EU stipulating human vibration control measures to be legislated by 2005 in all European Union countries. This directive mandates a whole-body vibration exposure limit of 1.15 m/s^2, and an action level of 0.5 m/s^2 for an equivalent eight-hour exposure period when measured according to ISO 2631-1[3]. There is a real concern that a number of earthmoving vehicles used in the South African mining industry, such as articulated dump trucks, which are also being exported to Europe, will expose operators to substantially higher levels

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of vibration than that allowed by this directive. The limit values may also be used in SA court cases as the current 'state-of-the-art', which will require SA companies to, at least, attempt to reduce WBV levels to below these limits in order to protect the health and safety of workers. Although no formal regulations are in place in SA to control the exposure of workers to WBV, the enforcement of the action and limit values set by this EU directive may be used in future litigation in SA as the state-of-the-art and hence demonstrate negligence by employers who knowingly have exposed workers to higher levels of vibration.

The primary contact point for the transmission of WBV to drivers of industrial vehicles is through the seat cushion, directly beneath the ischial tuberosities ('sit bones'), Griffin[4]. The seat is therefore the last suspension mechanism that can isolate the driver. Proper seat selection can significantly contribute to a reduction of the levels of WBV transmitted to the driver of an industrial vehicle. The level of vertical vibration on the seat-top of an occupied seat will be influenced by several factors, including the type of road, vehicle suspension, speed of travel, the physical size of the driver or operator, the type of vehicle, and the seat's dynamic characteristics.

Suspension seats are used in several mining and earth-moving vehicles and consist of a low-stiffness suspension mechanism (usually some type of spring and a damper) mounted below a relatively firm seat cushion. They have the capability to provide substantial vibration attenuation in some environments but this is not the general rule as the efficiency of a seat depends on the vibration spectrum as well as the seat dynamics. The usefulness of a particular suspension seat is determined by the frequency spectrum and amplitude distribution of the specific environment (Griffin[4]).

Seat transmissibility is the non-dimensional ratio of the amplitude of the vibration at the seat-human interface to the amplitude of the vibration of the excitation at the base of the seat expressed as a function of the vibration frequencies. It is used to characterize the ability of a seat to isolate (and also amplify) road vibrations. A seat will have different transmissibility characteristics depending on the type of input vibration. This is primarily due to the nonlinearity of the seat, (Wu and Griffin[5]), i.e. changes in the magnitude of the vibration spectrum at the seat base can change the frequency content, the resonance frequency, and the magnitude of the vibration spectrum on the top of the seat.

To obtain transmissibility estimates at all the frequencies, a broadband frequency input vibration should be used in the laboratory measurements. Two levels of broadband input vibration will help to indicate the level of nonlinearity in a seat. Transmissibility data with broadband input vibration can be used only to compare different seats with each other. Nonlinear characteristics in the seats prevent the use of these transmissibility data for determining any absolute values of peak transmissibility and attenuation efficiency for an arbitrary vibration input.

SEAT (seat effective amplitude transmissibility) value is a metric used to characterize the vibration and shock isolation efficiency of a seat. SEAT value is a ratio of the vibration experienced on the top of the seat to the input vibration at the base of the seat.

ISO 7096[6] stipulates SEAT values for specified subject weight categories that cater for different countries and industries for the testing of suspension seats, mainly for industrial-type vehicles. To test seats to be fitted in a particular vehicle for use in the South African industrial environment, it will be useful to select subjects that fit the most common profile of the drivers in the chosen industry. Using three subjects will help to distinguish which of the subjects display peculiar characteristics if there are significant discrepancies. The variation in human biodynamic behaviour can mean that there might be significant differences in the transmissibility functions between two subjects, even when their weight, build, gender and fitness levels are the same.

A set of seat selection guidelines will assist manufacturers of industrial vehicles to promote safer working environments through reduced WBV control. A prerequisite for these guidelines is that they must be practical and easy to implement.

The aim of this study was to develop a set of seat selection guidelines based on laboratory measurements of seat transmissibility, the actual vibration inputs one could expect in the field, and the computation and comparison of SEAT values. The proposed guidelines are based on a case study where six seats were evaluated for application in an articulated dump truck (ADT). The SEAT values and transmissibility functions were measured on the dynamic seat testing facility (DSTF) at Stellenbosch University. SEAT values were computed using the floor vibrations measured in a typical ADT as input, representing road vibration affecting the seat selection in the South African mining industry. Finally, a set of seat selection guidelines is presented.

Seat transmissibility experiments

Seat transmissibility functions are defined as the ratio of the amplitude of vibration at the base of the seat (floor of the vehicle) and the amplitude of vibration transmitted to the occupant taken as the vibration of the seat-person interface. These functions are normally expressed as a function of frequency to indicate the interaction between the human and seat's individual dynamics.

For this study six suspension seats from five different manufactures were studied. The seats were from various suppliers but all made use of air-springs instead of metal coils. Some of the seats had adjustable dampers that could be switched on or off. The selection of seats is described in Table I.

Table I

Description of seats tested

Seat	Description
A	Air-suspension, no damper adjustment
B	Air-suspension, no damper adjustment
CD	Air-suspension, damper disengaged (off)
CE	Air-suspension, damper engaged (on)
DD	Air-suspension, damper disengaged (off)
DE	Air-suspension, damper engaged (on)
E	Air-suspension, no damper adjustment
F	Air-suspension, no damper adjustment

Seat transmissibility is known to have some dependence on the weight and size of the seat occupant. Two weight categories of test persons are suggested for seat transmissibility measurements in ISO 7096[6], namely the 'light person' and the 'heavy person'. The 'light person' is required to have a total mass of 52 kg to 55 kg, of which not more than 5 kg may be carried in a belt around the waist. The 'heavy person' is required to have a total mass of 98 kg to 103 kg, of which not more than 8 kg may be carried in a belt around the waist. Six subjects were selected for the seat transmissibility measurements, three in the 'light person' category and three in the 'heavy person' category, as defined in ISO 7096[6]. The subject characteristics are described in Table II.

The seats were all mounted rigidly to the platform. Prior to the tests, the subjects completed a consent form for participation in human vibration experiments and were informed of their rights and the possible adverse affects of WBV exposure. The test subjects were requested to assume the recommended posture as prescribed in ISO 7096[6] (refer Figure 1). The feet were placed on the footrest and the hands on the thighs in an upright, but comfortable posture.

The DSTF at Stellenbosch is a man-rated test set-up where human subjects can be tested while seated on the seat specimens. It is important to use human subjects in seat testing as the human biodynamics couple with the seat dynamics. Rigid masses and water or crash-test dummies can not be used for seat testing as they do not reproduce the impedance loading of the human body, resulting in unreliable results.

Occupied seat systems are nonlinear therefore more than one level of excitation needs to be considered (Griffin[4]) in order to give an indication of the extent of the nonlinearity, and even then the results may not be reliable. Two levels, 1 m/s^2 and 2 m/s^2, of root mean square (r.m.s.) acceleration, with a frequency range of 0–25 Hz, measured at the base of the seat were selected to obtain two transmissibility estimates for each seat. The spectra and levels were chosen to correspond with the amplitude of measured vibration data on the floor of a typical ADT.

The seats were conditioned to the weight of the test occupant by the person sitting in the seat for 5 minutes at the beginning of each test. A trial test was conducted to enable further conditioning of the seat for the dynamic test. The experiments at the two excitation levels were thereafter carried out in succession for each test subject. The room temperature during the experiment varied between 16°C and 22°C.

Table II

Characteristics of subjects used in seat characterization

Subject no.	Gender (male/female)	Total mass (as tested) [kg]	Height w/o shoes [m]
	Light subjects		
1	female	55.0	1.65
2	female	53.7	1.59
3	male	56.2	1.63
	Heavy subjects		
4	male	98.3	1.83
5	male	98.3	1.75
6	male	98.4	1.97

The transmissibility results were obtained from two vertical acceleration measurements, one at the base of the seat and the other at the seat surface. Vibration at the base of the seat (see Figure 2) was measured using a PCB Piezotronics single channel accelerometer (Model No. 353B33, SN 69345), secured by a screw-mount. A PCB Piezotronics seat-pad with triaxial accelerometers (Model No. 356B40, SN 21385), conforming to the calibration requirements of ISO 10326-1[7], was used for the acceleration measurements at the seat-top (see Figure 2). The seat-pad was taped to the top of the seat surface, approximately 128 mm from the backrest.

A computer-based data acquisition and analysis system, SigLab (version 3.2.6) was used to acquire the acceleration signals, along with MATLAB software programmes developed at Stellenbosch University for the DSTF. Data was acquired for a period of 204 seconds per measurement. The signals were low-pass filtered to prevent aliasing and sampled at 128 Hz (Bendat and Piersol[8]). Only data up to 30 Hz was used for the analysis.

The use of transmissibility functions to assess suspension seats

The transmissibility measurements were used to evaluate the use of suspension seats in an ADT of 40 ton load capacity that is commonly used on South African mines. A typical result for the transmissibility tests is shown in Figure 3 for seat C with the damper disengaged and using the low (1 m/s^2) excitation for the three light subjects, subjects 1, 2 and 3.

Figure 1—Seat test posture

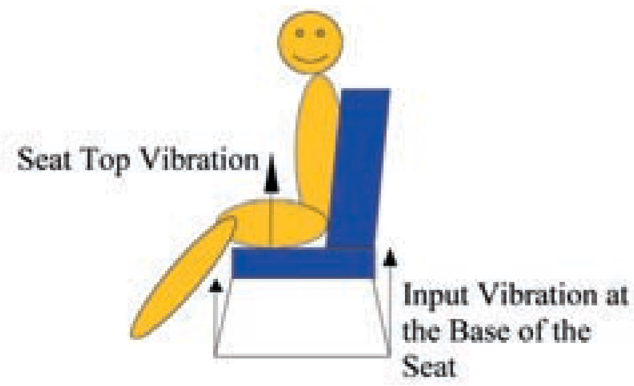


Figure 2—Person on seat with input vibration at the base of the seat and measured response at the seat top

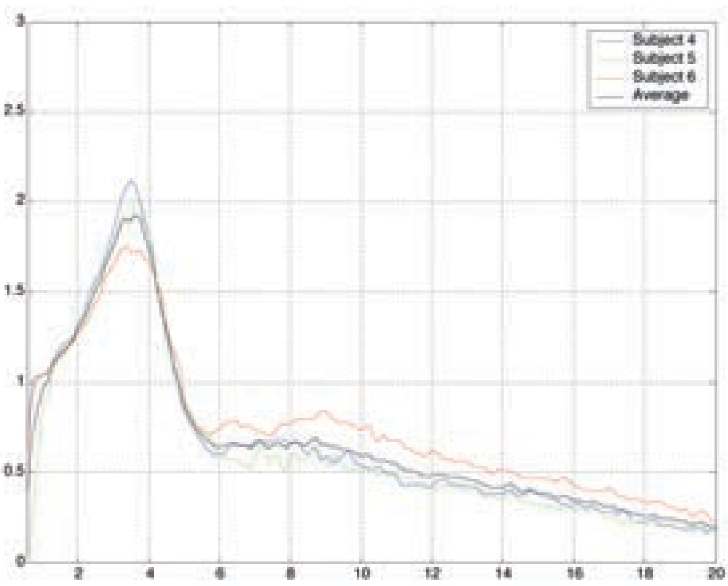


Figure 3—Typical seat transmissibility results

In Figure 3 the inter-subject variation can clearly be seen in that subject 3 (red curve) differs substantially from subjects 1 (blue) and 2 (green). The black curve represents the averaged transmissibility for this seat and is calculated by averaging the three individual transmissibility curves. The typical primary resonance at approximately 4 Hz can be seen as well as secondary resonance around 8 Hz. The first resonance is the dominant motion of the human (mass) on the seat (spring), although there is substantial coupling to the human body's inherent dynamics. The secondary resonance is commonly believed to be associated with the upper legs' movement relative to the seat.

The averaged transmissibility graphs for all the seats are shown in Figure 4. In these figures the various characteristics of the seats can be seen. Transmissibility curves for the light persons show some peculiar behaviour as some of the seats, A and E, have a transmissibility greater than 1 for most of the frequency range of interest. This may be due to the fact that these subjects were too light to load the seats sufficiently, or that the seats were constantly topping out (hitting the top bump-stop) due to the ride height these subjects selected because of their smaller stature.

For the heavy subjects the graphs are more in line with what one would expect and all the seats seem to function as suspension seats. Seats B and C, with a low resonance peak as well as small transmissibility at higher frequencies, seem to be the more effective seats. Seat F has the highest resonance peak and average attenuation at higher frequencies.

SEAT value estimation

The SEAT value is a ratio of the amount of vibration on the floor of the cabin, where the seat is attached, to the amount of vibration measured at the interface between the occupant and the seat (seat top). It can be calculated using the following equation, (Griffin[4]). This value can be estimated from the measured transmissibility functions by using Equation [1].

$$SEAT = \left[\frac{\int G_{ff}(f) \left| H_{fs}(f) \right|^2 W_i^2(f) df}{\int G_{ff}(f) W_i^2(f) df} \right]^{1/2} \quad [1]$$

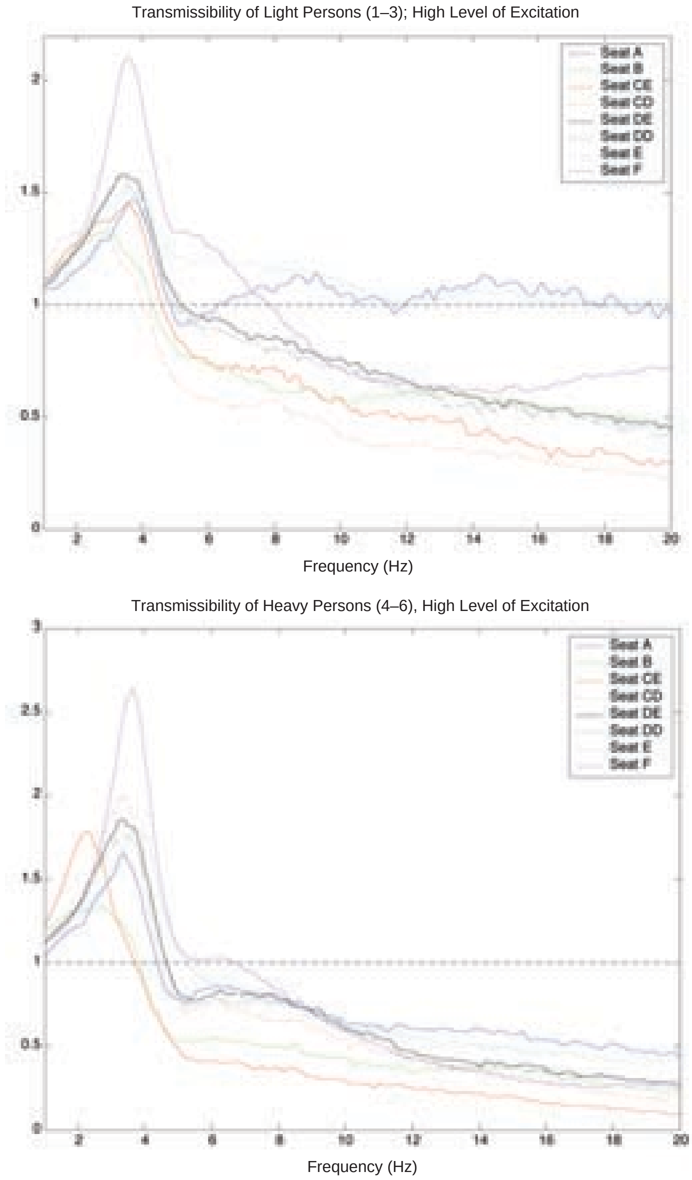


Figure 4—Averaged seat transmissibility graphs for all seats

Where $G_{ff}(f)$ is the power spectral density of the vibration on the floor of the cab, $|H_{fs}(f)|$ is the transmissibility function of the seat as measured with an occupant, and $W_i(f)$ is the relevant frequency weighting filter for the human response to the vibration in the position and direction that is of interest. The appropriate weighting filter for vertical vibration on the seat cushion is $W_k(f)$ a defined in ISO 2631-1[3].

According to ISO 7096[6] the EM1 input spectral class, defined as 'articulated or rigid frame dumper > 4 500 kg' is the appropriate input spectrum to use to evaluate the suitability of a specific suspension seat for this type of vehicle. Most of the energy of EM1 is concentrated between 1.5 Hz and 2.5 Hz, as shown in Figure 5. The r.m.s. level of class EM1 is 2.21 m/s^2 but with most of the energy concentrated in the frequency range between 1.5 and 2.5 Hz. Due to the nonlinear behaviour of suspension seats, it is not always possible to estimate the SEAT value for this input using the measured transmissibility functions. In an attempt to compare the seats, without conducting a full series of tests according to ISO 7096[6], the SEAT values were estimated using transmissibility functions obtained from a modified version of spectral class EM5, as shown in Figure 6. The preliminary SEAT values are shown in Table III. (As very few light subjects are found in SA, only the results for the heavy subjects are shown.)

The results in Table III were compared with data obtained from a seat supplier and some preliminary tests, using EM1 in the time domain. The SEAT values for seat D were previously measured as 0.79 for heavy subjects. This is less than the 1.00 and 1.24 values predicted using the transmissibility functions. In addition, for seat C the SEAT values were measured as 0.98 for CD and 0.77 for CE, which is also less than predicted in Table III. It can therefore be concluded that SEAT values for suspension seats subject to large displacements at low frequencies cannot be estimated reliably

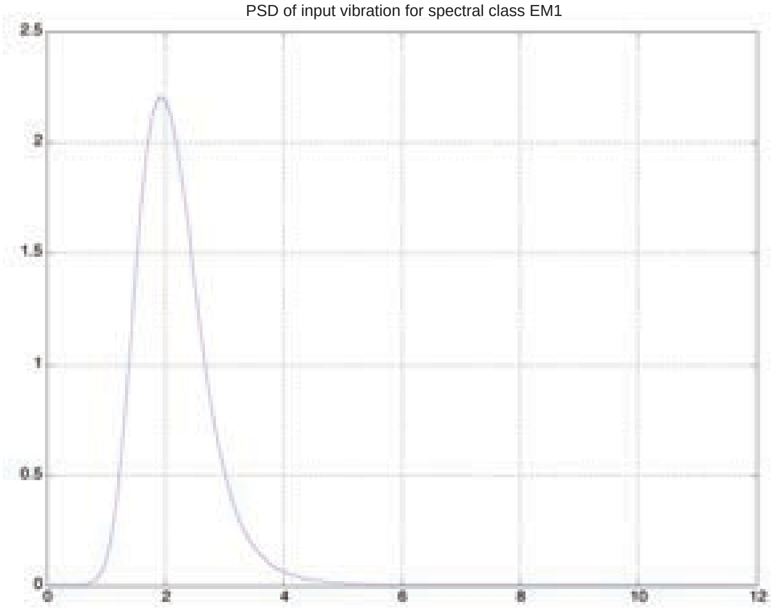


Figure 5—PSD of input vibration for spectral class EM1 according to ISO 7096[6]

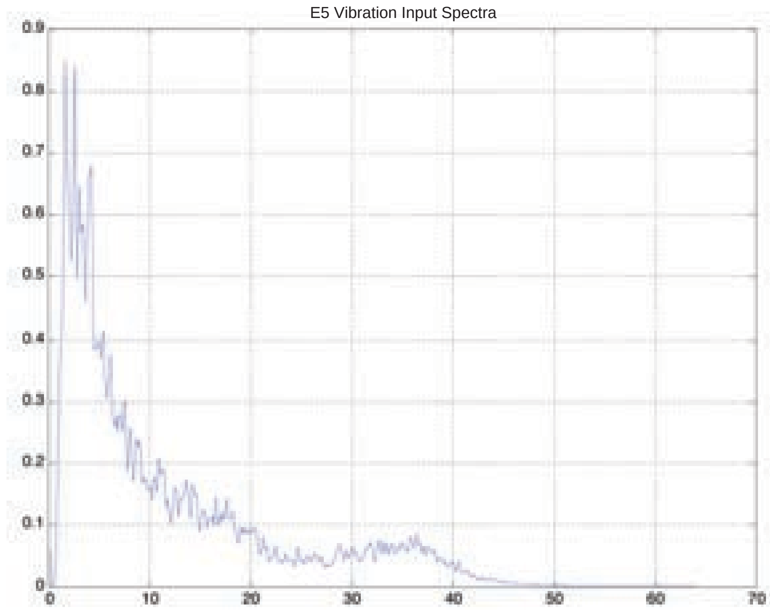


Figure 6—PSD of input vibration spectrum approximating EM5 measured on the platform

Table III

Computed SEAT Values for EM1 input spectra for the 'heavy' subjects

Seat	Subject 4	Subject 5	Subject 6	Average*	Average Transm.#
B	1.24	1.13	1.16	1.18	1.18
CD	1.36	1.42	1.33	1.37	1.37
CE	0.81	0.91	0.84	0.85	0.85
DD	1.00	1.00	1.02	1.01	1.00
DE	1.22	1.22	1.28	1.24	1.24
F	1.58	1.53	1.55	1.55	1.55

* This average is calculated as the numerical average of the three individual SEAT values for heavy persons.
# This value is obtained using the averaged transmissibility curve for heavy persons

from seat transmissibility functions, even if they were obtained with excitation levels comparable to the anticipated input. This is due to the nonlinear behaviour of these types of seats when subjected to high levels of vibration.

Operational vibration data were obtained on an articulated dump truck to use in the selection criteria of a suitable suspension seat. These data were measured on the floor of the cab over a variety of road conditions. For these tests the truck was unloaded. (Previous measurements have shown that unloaded trucks vibrate more than loaded trucks as a result of the increased inertia of the load.) The measured vibration data were analysed to obtain representative power spectral densities that represent the input vibration spectrum at the base of the seat during typical operational conditions. The following operating conditions are represented by this data:

- Travelling at moderate speed on a tar road (0.69 m/s^2 r.m.s.)
- Travelling at low speed on a bad gravel road (2.09 m/s^2 r.m.s.)
- Travelling at moderate speed on a corrugated gravel road (2.32 m/s^2 r.m.s.)

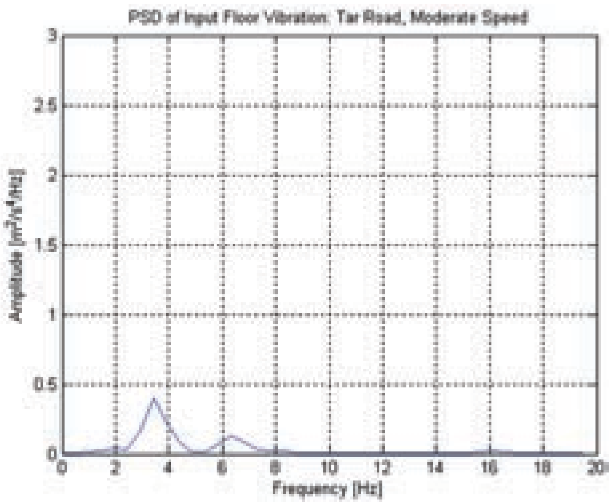
The input spectra for these different conditions are shown in Figure 7. Here one clearly sees the rigid body modes at approximately 3 Hz and the so-called wheel-hop modes at 10–14 Hz.

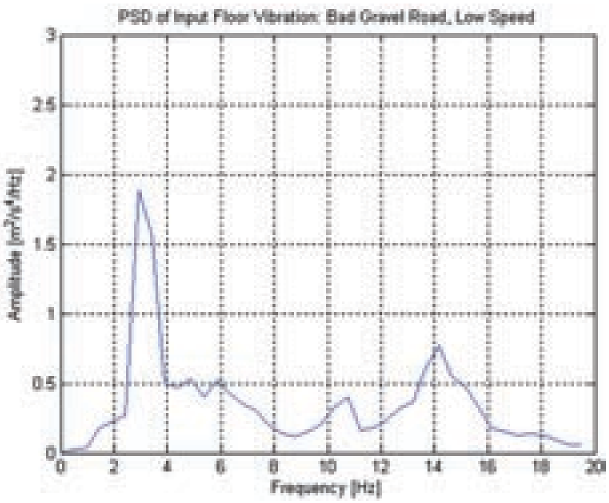
The SEAT values for the different seats for these road inputs were calculated according to Equation [1] using the averaged transmissibility functions for the light and heavy persons. The results are listed in Table IV.

Seat selection

Seat selection criteria include a number of aspects, such as static comfort, ergonomics, durability, maintainability, cost, aesthetics, etc. The seat selection criteria presented in this paper address only one particular aspect, *dynamic comfort*, in order to reduce WBV exposure to improve both ride comfort and occupational health and safety.

Optimal dynamic response of a seat depends on both the vibration spectra of the environment and the relevant criteria (i.e. to minimize the most important adverse effects of the vibration). The relevant criteria in the European Directive 2002/44/EU regarding WBV exposure were considered in the development of the seat selection guidelines. For suspension





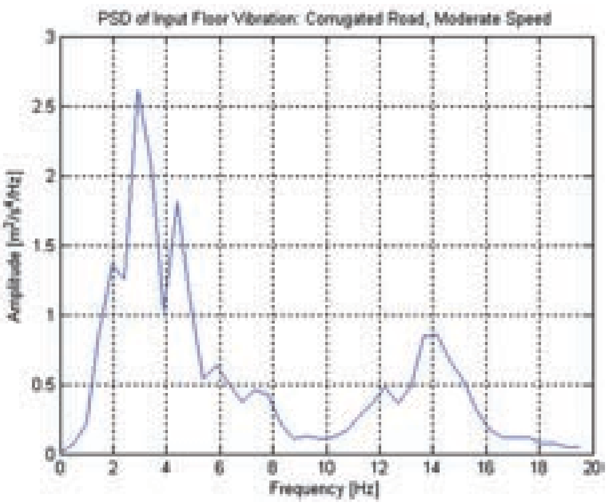


Figure 7—PSD plots of input floor vibration in the cab of an empty ADT

Table IV

Computed SEAT values for measured road inputs

Seat	Light Persons (Subjects 1–3)		
	Tar road	Bad gravel	Corrugation
A	1.38	1.13	1.11
B	1.23	0.90	0.77
CD	**1.07***	**0.80***	**0.63***
CE	1.21	0.93	0.75
DD	1.36	1.03	0.85
DE	1.37	1.06	0.88
E	1.35	1.20	1.14
F	1.67	1.27	1.06
SEAT	**Heavy Persons (Subjects 4–6)**		
	Tar road	**Bad gravel**	**Corrugation**
A	1.55	1.00	0.85
B	1.19	**0.78***	0.62
CD	1.39	1.09	0.87
CE	**1.10***	0.81	**0.58***
DD	1.48	1.05	0.83
DE	1.51	1.08	0.86
E	1.47	1.08	0.88
F	1.95	1.31	1.06

* The lowest SEAT value for each operational condition

seats the SEAT value stipulations according to ISO 7096[6] were also considered.

There are several factors that determine seat dynamic efficiency such as the input vibration at the base of the seat, seat occupant characteristics, and seat dynamics. The input vibration at the base of the seat is determined by the road input, vehicle speed, and vehicle's dynamic characteristics. Seat occupant characteristics are mainly influenced by the weight and posture of the person.

Seats are selected based on the 8-hour equivalent vibration exposure level on the seat surface evaluated according to ISO 2631-1[3], the SEAT values, and the transmissibility functions of the seats. These values and ratios are measured or evaluated for a seat from input vibration spectra at the base of the seat that are simulated on the platform of a suitable seat testing facility (in accordance with ISO 103261-1[8]), and seat occupant characteristics.

It is recommended for seats to be selected based on low SEAT values (preferably below 1), low peak transmissibility and low transmissibility at higher frequencies (10–20 Hz). From published data and the seat transmissibility measurements in this project it might be reasonable to recommend that the seats have a peak transmissibility ratio of less than 2.5 when measured using a broadband vibration input (Griffin[4]). The transmissibility ratios for the seats at frequencies between 10 Hz and 25 Hz can be recommended to be below 0.5 for the same vibration input.

Seats are evaluated for compliance of the 8-hour vibration exposure levels with the levels in the European Directive 2002/44/EU. In the case of suspension seats, the seats should also qualify as suspension seats according to ISO 7096[6]. Seat comparisons are based on the SEAT values and transmissibility functions of the seats for the given vehicle, operating conditions, and operator profile.

Seats can either attenuate or amplify vibration. The seat having the optimum dynamic properties is one which is most capable of minimizing WBV of the occupant in the relevant vibration environment.

Seat selection guidelines

A preliminary set of seat selection guidelines are given in the appendix.

Recommendations and future work

It is recommended that a proper seat selection process is followed by manufacturers, suppliers and users of industrial vehicles in order to minimize the WBV exposure and ensure that the seat functions as a vibration isolator and not a vibration amplifier for the operating conditions of the vehicles. If the proposed guidelines are followed by industry, it should result in a significant reduction of WBV exposure in the SA industry.

Based on the fact that the level of WBV exposure in an industrial vehicle depends on the vehicle dynamics, the seat dynamics and the operating conditions, the following major and minor recommendations for future work are proposed for the South African industry.

Major recommendations:

- Commission a study to evaluate the performance of both suspension and non-suspension seats to attenuate vibration in the South African industrial environment. Such a study should include a component to assess the current practice in industry regarding the operation and maintenance of suspension seats

- Investigate seats under shock loading representative of the operating conditions of the vehicle. This may be of particular interest for some operating conditions in the mining and earth-moving sectors where the vibration frequently includes large peaks due to the prevailing road conditions
- An epidemiological study of SA drivers and operators of vehicles that are known to expose drivers to high levels of vibration
- Develop a classification for fit for work to eliminate driver fatigue, a major cause of accidents.

Minor recommendations:

- Conduct measurements of WBV through backslap, as it is possible for vibration in the vertical axis at the seat input to produce vibration in another axis on the seat
- Investigate the effects of dampers on the dynamic performance of seats
- A seat's characteristics can change during its lifetime. It might be beneficial to study or carry out investigations on the dynamic performance of seats over the expected lifespan of the vehicles.

Conclusions

In this study care was taken to obtain reliable seat transmissibility data from a variety of input spectra. These functions were then used to evaluate the vibration attenuation properties of different seats and to compare their effectiveness for application as appropriate seating systems for articulated dump trucks. The transmissibility functions were used to estimate the SEAT values for the actual measured vibration input data for the comparison of seats.

Results show that transmissibility functions obtained with broadband vibration input cannot be used to estimate SEAT values for inputs where the vibration energy is concentrated between a few Hertz in the low frequency range. It is therefore required to determine the SEAT values for the spectral classes in ISO 7096 (2000) from time domain data.

It is, however, useful to compare different seats using the measured seat transmissibility functions as well as comparing the SEAT values for different measured road input data.

Current seat selection procedures for WBV control in vehicles used in the SA industry need to be replaced with a set of seat selection guidelines in order to ensure that drivers are adequately protected from harmful vibrations, to improve productivity in industry, and to enable SA vehicle manufacturers to market their vehicles in Europe. A set of design guidelines for seat selection to control WBV has been proposed in this paper.

Future work should include comprehensive measurements of the operating vibration conditions in the South African industry as well as epidemiological surveys to establish the extent of WBV-related disorders among drivers and operators in South Africa.

Acknowldegments

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Appendix—Seat selection guidelines to reduce whole-body vibration exposure in mining vehicles

Introduction

The operators of industrial vehicles are exposed to low-frequency vibration levels that can adversely affect occupational health and safety. The seat is the last suspension mechanism that can isolate the driver. Selecting an appropriate seat has the potential to significantly reduce whole-body vibration exposure levels to the operators. The efficiency of a seat in attenuating the vibration transmitted to the driver of an industrial vehicle is dependent on the type of vehicle and the type of operations carried out. Seats thus need to be selected in accordance with the dynamic characteristics of the vehicle and the vibration environment of the relevant industry.

General

This document provides a method for selecting the best seat for the control of vertical whole-body vibration of the operator of an industrial vehicle between the frequencies 1 Hz and 20 Hz (as most industrial vehicles impart significant vertical vibration up to 20 Hz). The laboratory test conditions and test procedures of seat vibration is according to ISO 10326-1 (1992). The evaluation of suspension seats is according to ISO 7096 (2000). Whole-body vibration measurement and evaluation is according to ISO 2631-1 (1997).

The selection criteria aim to reduce the vertical vibration exposure level at the seat top for an equivalent 8-hour exposure period. The European Directive 2002/44/EU mandates a vibration action level of 0.5 m/s^2 and a vibration exposure limit of 1.15 m/s^2, for an equivalent 8-hour exposure period. The stipulations in this directive will be used to evaluate vibration exposure levels in the industrial vehicles.

This document contains guidelines for seat selection and does not contain details of procedures for vibration measurement and evaluation.

The factors that influence the vibration at the seat top of an industrial vehicle are:

- Input vibration at the base of the seat
- Seat occupant characteristics
- Seat dynamic characteristics
- Frequency weighting functions (according to ISO 2631-1 (1997))
- Vibration exposure time.

The input at the base of the seat, the seat occupant characteristics, and the seat dynamic characteristics influence the vibration level at the seat top. The frequency weighting function and the exposure time are used to determine the whole-body vibration exposure level for an 8-hour exposure period from the seat top vibration.

This document contains guidelines for the listed factors that are considered to influence the vibration exposure level at the seat top, and concludes with a seat selection checklist.

The seat testing guidelines depend on the availability of an appropriate man-rated seat testing facility with a platform and servo-hydraulic actuator for the simulation of input vibration at the seat base. The seat testing equipment should comply with the requirements in the international standard ISO 10326-1 (1992).

Input vibration at the base of the seat

The input vibration at the seat base is determined by:

- Operational input vibration: the power spectral density function and/or time data of the operational vibration measured on actual vehicles in typical applications
- ISO 7096 (2000) input vibration: the power spectral density function of the relevant input spectral class (EM1 to EM9), for suspension seats, as defined in the standard.

Operational input vibration

The terrain over which the vehicle is driven and the tasks carried out determine the input vibration at the base of the seat. Therefore select the applicable type of vehicle, industry and operating conditions for which a seat is required.

Measure the vertical vibration at the seat base for a selection of operating conditions. Acceleration measurements can be used to determine the vertical vibration at the seat base. It is recommended that at least three vertical acceleration measurements be taken in order to evaluate the pitch and roll motion of the vehicle vibration. The measurements of the vertical acceleration should be converted to a set of estimates of the vertical vibration at the seat base for each operation. It is sufficient to use a rigid body dynamic approximation for the estimation of the vibration input at the seat base.

Compute the root mean square values of the vertical vibration input estimates at the seat base for each of the operations. Determine the highest root mean square value acceleration (H) and the lowest root mean square value acceleration (L).

The operational input vibration is the average vertical vibration for the particular selection of operations. It is recommended that the operational input vibration be represented by time data and power spectral density functions.

The power spectral density functions of vehicle vibrations at the seat base in the vertical direction usually exhibit primary resonance between 1 Hz and 2 Hz due to the rigid body modes of the vehicle. Secondary resonance due to the wheel-hop modes can occur in the frequency range 10–15 Hz.

ISO 7096 (2000) input vibration

For suspension seat applications, select the appropriate input spectrum (EM1 to EM9) for the applicable vehicle class, e.g. the EM1 input spectral class is defined for ‘articulated or rigid frame dumper > 4 500 kg’. This spectrum is to be used to determine if the seat qualifies as a suspension seat according to ISO 7096 (2000).

The input spectra EM1-EM9 are based on measurements taken *in situ* on earthmoving machinery used under severe but typical operating conditions. The input spectra represent the vibration envelope of the vehicles within each class. The input spectra are represented by power spectral density functions.

Seat occupant characteristics

Seat transmissibility functions and SEAT values for the seats should be measured using at least three test subjects with characteristics similar to the characteristics of the average operator of the vehicle in the selected industries. Characteristics of the average operator will be determined from relevant anthropometrical data for the population segment that is most common to the drivers of the vehicle for the combination of operations and industries. The seat occupant shall be characterized by weight. It is also useful to record the height and gender of the subjects.

All seat testing must be conducted using human subjects and not rigid masses or dummies as they do not replicate the biodynamics of the human body.

Seat dynamic characteristics

The seat dynamic characteristics are described by:

- Seat transmissibility functions
- Seat effective amplitude transmissibility (SEAT) values according to ISO 10326-1 (1992).

Seat transmissibility function and SEAT values can be measured on a seat test facility, but it must be done with human subjects to obtain reliable results.

Seat transmissibility function

Two levels, at H and L, of random broadband frequency vibration should be used as input to yield two transmissibility functions for each seat.

Obtain reliable transmissibility measurements with the two levels of broadband vibration input for all of the three test subjects. The individual transmissibility functions of the subjects obtained with the two broadband vibration inputs should be used to compute two average transmissibility functions for each seat. (Note: compare the average transmissibility curve with the individual transmissibility curves of the subjects and ensure that the average curve is a consistent representation.)

The pairs of transmissibility curves should be used to determine the nonlinear effects of each seat.

The transmissibility functions of the seats should be used to compare the dynamic performance of all the potential seats for the vehicle. It is sufficient to use one set of the average transmissibility functions of the seats for the comparisons (in general the transmissibility results for the H level broadband vibration are used). The transmissibility at resonance, the resonance frequency and the attenuation of vibration at high frequencies can be used to evaluate the most suitable seat from the seat transmissibility functions.

Seat effective amplitude transmissibility (SEAT) value

SEAT values can be used to indicate the efficiency of a seat in isolating the operator of a vehicle from the vibration on the floor of the cabin. SEAT values should be measured according to the measurement procedures in ISO 10326-1 (1992). The SEAT values can be measured from the root mean square values of the frequency-weighted (see Guideline No. 6) acceleration signals or vibration dose values in case of large transient peaks in the vibration signal.

SEAT values are measured using the operational input vibration. Compare SEAT values obtained with the operational input vibration of the vehicle. Select the seats with the lowest SEAT values for the operational input vibration.

In the evaluation of suspension seats, SEAT values should also be measured using the ISO 7096 (2000) input vibration. Assess the SEAT values of each seat according to ISO 7096 (2000).

Vibration exposure level

Vibration exposure levels should be calculated for an 8-hour equivalent day.

Frequency weighting should be used to determine the human response to vibration exposure. The frequency weighting should be according to ISO 2631-1 (1997) and is W_k for the vertical vibration at the top of the seat. The typical vibration exposure period of each operation as observed in the selected industries should be recorded in hours.

The frequency-weighted acceleration for the equivalent 8-hour exposure period should be calculated according to ISO 2631-1 (1997).

Seat selection checklist

The seat selection criteria are:

Seat selection criteria	Yes	No
Does the seat have acceptable transmissibility at resonance? (Transmissibility ratio below 2.5?)		
Does the seat have satisfactory attenuation at frequencies above 10 Hz? (Transmissibility ratio below 0.5?)		
Does the seat qualify as a suspension seat according to ISO 7096 (2000)?		
Does the seat have a relatively low SEAT value for the operational input vibration compared to other seats?		
Does the 8-hour vibration exposure level exceed the action level of 0.5 m/s^2 prescribed in the European Directive 2002/44/EU?		
Does the 8-hour vibration exposure level exceed the exposure limit of 1.15 m/s^2 prescribed in the European Directive 2002/44/EU?		

A block diagram describing seat selection is included at the end of this guide.

References

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Flow chart of Seat Selection Guidelines