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EFFECT OF SEATING ON EXPOSURES TO WHOLE-BODY VIBRATION IN VEHICLES

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The vibration isolation efficiency of seating has been evaluated in 100 work vehicles in 14 categories (cars, vans, lift trucks, lorries, tractors, buses, dumpers, excavators, helicopters, armoured vehicles, mobile cranes, grass rollers, mowers and milk floats). Seat isolation efficiency, expressed by the SEAT value, was determined for all seats (67 conventional seats and 33 suspension seats) from the vertical acceleration measured on the floors and on the seats of the vehicles.

For most categories of vehicle, the average SEAT value was less than 100%, indicating that the average seat provided some attenuation of vibration. However, there were large variations in SEAT values between vehicles within categories. Two alternative vibration frequency weightings (W_b from BS 6841, 1987; W_k from ISO 2631, 1997) yielded SEAT values that differed by less than 6%. Overall, the SEAT values determined by two alternative methods (the ratio of r.m.s. values and the ratio of vibration dose values) differed by less than 4·5% when using weighting W_b, although larger differences may be expected in some situations. The median SEAT value for the suspension seats was 84·6%; the median SEAT value for the conventional seats was 86·9% (based on weighting W_b and the ratio of r.m.s. values).

Predicted SEAT values were obtained assuming that each seat could be interchanged between vehicles without altering its transmissibility. The calculations suggest that 94% of the vehicles investigated might benefit from changing the current seat to a seat from one of the other vehicles investigated. Although the predictions are based on assumptions that will not always apply, it is concluded that the severity of whole-body vibration exposures in many work environments can be lessened by improvements to seating dynamics.

1. INTRODUCTION

Exposures of seated persons to whole-body vibration are influenced by seating dynamics. In some environments the dynamic response of the seat can be a factor most easily used to control human exposure to whole-body vibration. However, seats can increase, as well as decrease, vibration. The extent of the variation in the dynamic performance of seats in work vehicles (i.e., the extent to which they attenuate or amplify exposure to whole-body vibration) is not known. Knowledge of seat performance in a wide range of working environments in which operators of vehicles are exposed to vibration is required to identify the extent to which the seating dynamics influence occupational exposures to whole-body vibration.

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Conventional seats (seats with foam and metal, or rubber, springs) have vertical resonances in the region of 4 Hz. Vertical vibration is amplified around this frequency and at all lower frequencies. The amplification at resonance can be a factor of two, or more. Only at frequencies greater than about 6 Hz will conventional seats attenuate vertical vibration. The amplification below this frequency and the attenuation above this frequency varies between seats. At present, there are no general standards for evaluating the dynamic performance of such conventional seats, although some internal standards are used within the automotive and rail industries.

"Suspension seats" have a separate suspension mechanism (containing a spring and a damper) to produce a low resonance frequency and isolate vibration at frequencies lower than can be isolated without the suspension mechanism. The resonance frequency varies between seats (depending on the spring stiffness and the mass of the seat and subject) but is often approximately 2 Hz. The amplification at resonance, and the attenuation at frequencies well above resonance, is controlled by a damper.

The isolation efficiency of seats can be determined using the SEAT value ("seat effective amplitude transmissibility" [1–3]). The SEAT value expresses the "ride" that is experienced when sitting on a seat compared to the "ride" that would be experienced on a rigid seat: SEAT values less than 100% indicate an overall improvement in the "ride" whereas values greater than 100% indicate that the seat has degraded the ride. In practice, it is not necessary to measure with a rigid seat: SEAT values are calculated from the ratio of the frequency-weighted acceleration occurring on the surface supporting the occupant to the frequency-weighted acceleration entering the supports of the seat where it is connected to the vehicle. If either the input or the output motion contains shocks, the SEAT value is determined using the vibration dose value, VDV [4, 5].

With a large variation in transmissibility between seats, it seems likely that the selection of a seat may be a prime factor in controlling occupational exposures to whole-body vibration. A simple approach to considering the extent to which improvements can be made is to investigate the extent to which swapping seats in current vehicles would lessen the SEAT values. Although this cannot always be achieved due to various physical limitations, the benefits can be estimated from calculations.

The main objective of this study was to measure floor and seat vibration for 100 work vehicles, calculate the seat isolation efficiencies for each vehicle and investigate whether ride could be improved in each vehicle by fitting a seat having the dynamic response of that measured in any of the other 99 vehicles. Subsidiary objectives of the study included determining the effect on SEAT values of using alternative frequency weightings (W_b or W_k) or alternative methods of averaging (r.m.s. or VDV).

2. EQUIPMENT AND PROCEDURE

Measurements of acceleration were made in 100 vehicles comprising 14 different categories. The different categories and numbers of vehicles in each category are shown in Table 1. The operating conditions for the 100 vehicles, including speed of travel, terrain traversed and type of seat in each vehicle, are shown in Appendix A. The vehicles were driven over the most suitable and appropriate surface relevant to work within each vehicle. For example, cars and lorries were driven over roads while sit-on mowers were generally driven over grass.

Acceleration was measured in the front seat, mostly the driving seat. The results presented in this report were obtained from two channels of acceleration: vertical acceleration beneath the seat and vertical acceleration on the seat surface beneath the seat

TABLE 1

Number and category of vehicles used in the study

Category	Number of vehicles
Car	25
Van	9
Lift truck	11
Lorry	16
Tractor	7
Bus	10
Dumper	4
Excavator	4
Helicopter	1
Armoured vehicle	4
Mobile crane	2
Grass roller	1
Mower	3
Milk float	3

occupant. Measurements of acceleration in three axes on the seat pan and fore-and-aft vibration on the backrest are presented elsewhere [6].

Vibration was measured using piezoresistive full-bridge accelerometers (Entran model type EGCSY-240D-10). An aluminium mount containing a vertically orientated accelerometer was secured to the vehicle floor beneath the seat. A semi-rigid mounting disc conforming to ISO 10326-1 [3] was used to measure seat vibration.

The signals from the accelerometers were acquired into a commercial computer-based data acquisition and analysis system, *HVLab* (version 3.81). The duration of the acquired signals was 60 s for most of the measurements. The acceleration waveforms were low-pass filtered at 100 Hz via anti-aliasing filters with an elliptical characteristic (Techfilter); the attenuation rate was 70 dB/octave in the first octave. The signals were then digitized into the *HVLab* data acquisition system at a sample rate of 400 samples/s using a PCL818 board.

3. ANALYSIS

3.1. FREQUENCY WEIGHTINGS

The acceleration time histories were frequency-weighted using the two weightings defined for evaluating exposures of seated persons to vertical vibration: W_b as defined in British Standard BS 6841 [4] and W_k as defined in International Standard ISO 2631 [5]. The two frequency weightings are shown in Figure 1. The differences between the two frequency weightings, W_b and W_k, have been explained by Griffin [7].

3.2. ROOT-MEAN-SQUARE VIBRATION MAGNITUDES AND VIBRATION DOSE VALUES

All acceleration time histories were frequency-weighted using either W_b or W_k, as defined in BS 6841 [4] and ISO 2631 [5], respectively.

Root-mean-square (r.m.s.) vibration magnitudes were calculated for the vertical vibration measured on the floor beneath the seats and on the surfaces of seats:

$$\text{root-mean-square, r.m.s. } (\mathrm{m/s^2}) = \left[\frac{1}{T}\int_0^T a^2(t)\,\mathrm{d}t\right]^{1/2}, \quad (1)$$

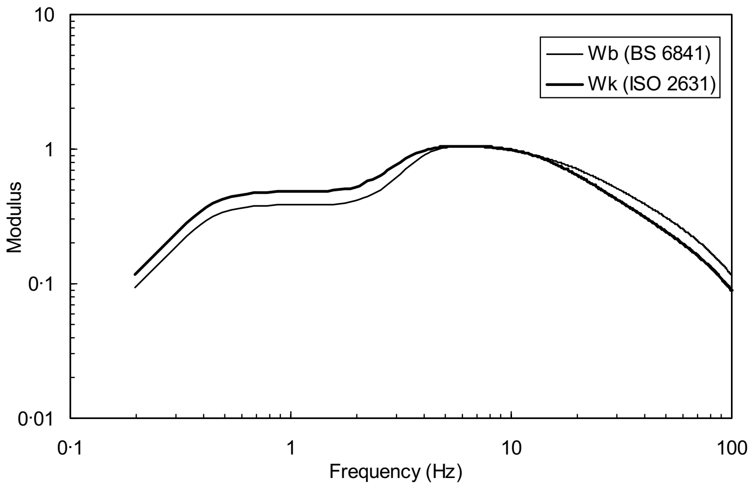

Figure 1. Frequency weightings W_b (BS 6841, 1987) and W_k (ISO 2631, 1997).

where $a(t)$ is the frequency-weighted acceleration time history (in m/s^2) and T is the measurement period (in s).

The vibration dose value, VDV, reflects the total, rather than the average, exposure to vibration over the measurement period and is considered more suitable when a vibration is not statistically stationary (e.g. it is intermittent or contains shocks):

$$\text{vibration dose value, VDV (m/s}^{1\cdot 75}) = \left[\int_0^T a^4(t)\,\mathrm{d}t\right]^{1/4}. \tag{2}$$

3.3. TRANSFER FUNCTIONS

Seat transfer functions were calculated between acceleration on the vehicle floor (i.e., the input) and acceleration measured on the seat surface (i.e., the output) using the "cross-spectral density function method". The "cross-spectral density function method" uses the proportion of output motion that is linearly correlated with the input motion. The transfer function $H_c(f)$, was determined from the ratio of the cross-spectral density of the input and output accelerations, $G_{io}(f)$, to the power spectral density of the input acceleration, $G_{ii}(f)$:

$$H_c(f) = \frac{G_{io}(f)}{G_{ii}(f)}. \tag{3}$$

3.4. SEAT VALUES

Seat effective amplitude transmissibility, SEAT, values can be calculated from either the root-mean-square, r.m.s., or the vibration dose value, VDV, of the frequency-weighted acceleration.

$SEAT_{r.m.s.}$ is the ratio of the frequency-weighted acceleration on the seat, $r.m.s._{seat}$, to the frequency-weighted acceleration on the vehicle floor, $r.m.s._{floor}$:

$$SEAT_{r.m.s.}\,(\%) = \frac{r.m.s._{seat}}{r.m.s._{floor}} \times 100\%. \tag{4}$$

$SEAT_{VDV}$ is the ratio of the frequency-weighted vibration dose value on the seat, VDV_{seat}, to the frequency-weighted vibration dose value on the floor, VDV_{floor}:

$$SEAT_{VDV}\ (\%) = \frac{VDV_{seat}}{VDV_{floor}} \times 100\%. \tag{5}$$

3.5. PREDICTION OF SEAT VALUES

The SEAT value is a measure of how well the transmissibility of a seat is suited to the spectrum of vibration entering the seat, taking account of the sensitivity of the seat occupant to different frequencies of vibration. The SEAT value of a seat therefore changes when a seat is exposed to a different spectrum of vibration. Assuming the transmissibilities of seats are independent of the characteristics of the vibration to which they are exposed (i.e., the transfer function is a reasonably good description of the linear part of the seat response, and the effects of vibration magnitude and spectrum are small), it is possible to use the transmissibility of a seat measured when exposed to vibration in one vehicle to estimate the SEAT value that would be obtained if the seat were exposed to the spectrum of vibration in other vehicles. For this process, accelerations for the surface of seat 1 (that was measured in vehicle 1) were then used to calculate accelerations for seat 1 if it were assumed to be in vehicles 2–100. The whole process was repeated for all combinations of seats and vehicles.

The procedure was carried out in the frequency domain:

$$SEAT\ (\%) = \frac{\left[\int_{f=0\cdot5}^{f=80} G_{ff}(f)\,|H(f)|^2\,S^2(f)\,\mathrm{d}f\right]^{1/2}}{\left[\int_{f=0\cdot5}^{f=80} G_{ff}(f)\,S^2(f)\,\mathrm{d}f\right]^{1/2}} \times 100\%, \tag{6}$$

where $G_{ff}(f)$ is the power spectrum of floor vibration, $H(f)$ is the seat transfer function, and $S(f)$ is the frequency weighting of human response to vibration.

Power spectral densities were calculated with a frequency resolution of 0·195 Hz and 48 degrees of freedom for a 60-s measurement period [8].

This estimation procedure assumes that the seats behaved linearly and that the transfer function could be defined at all frequencies. However, this is not always the case, especially in field conditions [2]. For a single-input–single-output linear system, vertical acceleration at the top of a seat would be caused by vertical acceleration at the base of the seat. For a single-input-single-output system, the coherency, $\gamma_{io}^2(f)$, between the input and the output is:

$$\gamma_{io}^2(f) = \frac{|G_{io}(f)|^2}{G_{ii}(f)\,G_{oo}(f)}, \tag{7}$$

where $G_{oo}(f)$ is the power spectrum of the output acceleration.

A coherence of unity indicates that the input and the output motions are linearly related. The presence of "noise" in the measurements, other inputs causing motion at the output, and non-linearities in the system can result in a coherency well below unity at some frequencies. This results in uncertainty in the measured seat transfer function: the uncertainty increases as the coherency between the floor and seat acceleration reduces (see section 3.3). Assuming a random error in the estimates of $G_{ii}(f)$, $G_{oo}(f)$ and $G_{io}(f)$, the standard error, σH, of the transfer function modulus $|H(f)|$ has been estimated as:

$$\sigma H = |H(f)| \sqrt{\frac{1 - \gamma_{io}^2(f)}{\gamma_{io}^2(f)\ \mathrm{d.o.f.}}}, \tag{8}$$

where $|H(f)|$ is the modulus of the transfer function, $\gamma_{io}^2(f)$ is the coherency between input and output, and d.o.f. is the number of degrees of freedom.

Confidence intervals can be calculated for the transfer functions using the standard error [9]. The confidence intervals (upper and lower) for the transfer function have been calculated as:

$$|H(f)| \pm \sigma H Z(\alpha/2), \tag{9}$$

where $Z(\alpha/2)$ is the percentage point on the normal distribution.

For 95% confidence limits, giving the uncertainty of the transfer function between the 2·5% and 97·5% probabilities, $Z(0{\cdot}025) = 1{\cdot}96$. It should be recognized that although this method of calculating confidence intervals is commonly used, it makes assumptions that may not always be applicable (e.g., the responses may be non-linear). The intervals calculated give a measure of uncertainty that may help to identify the relative accuracy of some estimates, but the absolute accuracy of the estimates is currently unknown. The non-linear components will often be unpredictable and dependent on the vibration input, seat adjustment and driver behaviour. For a suspension seat, the linear response will be expected to be more dominant than the non-linear response in the conditions for which the seat is primarily designed to operate (e.g., with moderate magnitude motions, no end-stop impacts, good seat adjustment).

4. RESULTS AND DISCUSSION

4.1. ROOT-MEAN-SQUARE VIBRATION MAGNITUDES

Figure 2 compares the unweighted r.m.s. acceleration magnitudes measured on the floors and the seats of the 100 vehicles. If the floor and the seat showed the same unweighted r.m.s. acceleration magnitudes, the data points in Figure 2 would lie on a 45° diagonal starting at the origin. Since more points are below the diagonal than above the line, the unweighted vibration magnitudes on the floor were usually greater than those on the seat pan. The point corresponding to floor vibration of 6·39 m/s^2 r.m.s. and seat vibration of 2·37 m/s^2 r.m.s. was vehicle number 63 (i.e., an armoured vehicle).

Figure 3 compares the frequency-weighted vibration magnitudes on the floor and on the seat using weighting W_b. The point with the highest vibration magnitude for both the floor and the seat (2·75 and 3·27 m/s^2 r.m.s., respectively), corresponds to an excavator (vehicle number 66).

Figure 4 compares the frequency-weighted vibration magnitudes on the seat using frequency weightings W_b and W_k. It is seen that the two frequency weightings produced similar vibration magnitudes for all vehicles.

For each category of work vehicle, the median frequency-weighted acceleration magnitudes on the floor and seat are shown in Table 2 and Figure 5. Data where there are small numbers of vehicles in a category should not be assumed to be representative of other vehicles in that category.

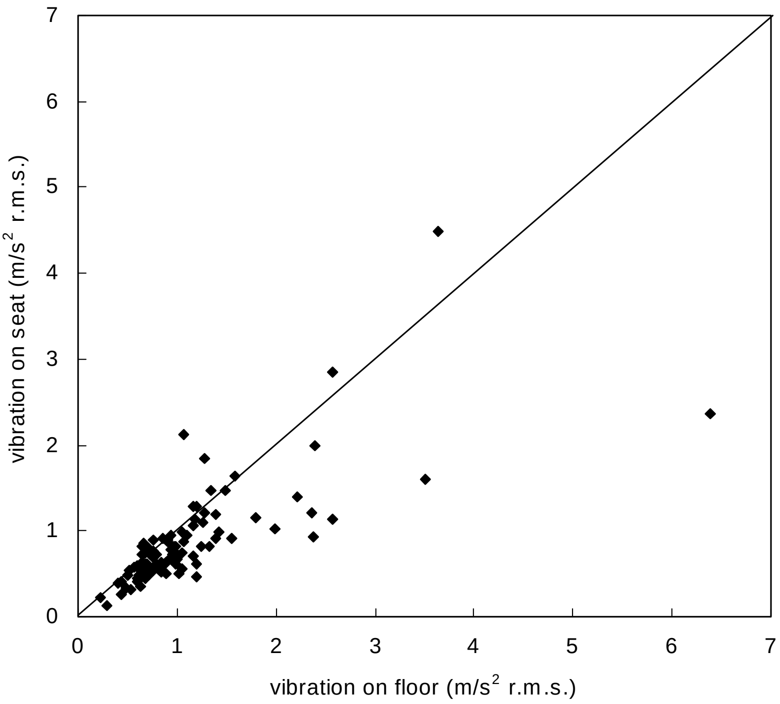

Figure 2. Unweighted vibration magnitudes measured on the floor and the seat for 100 vehicles.

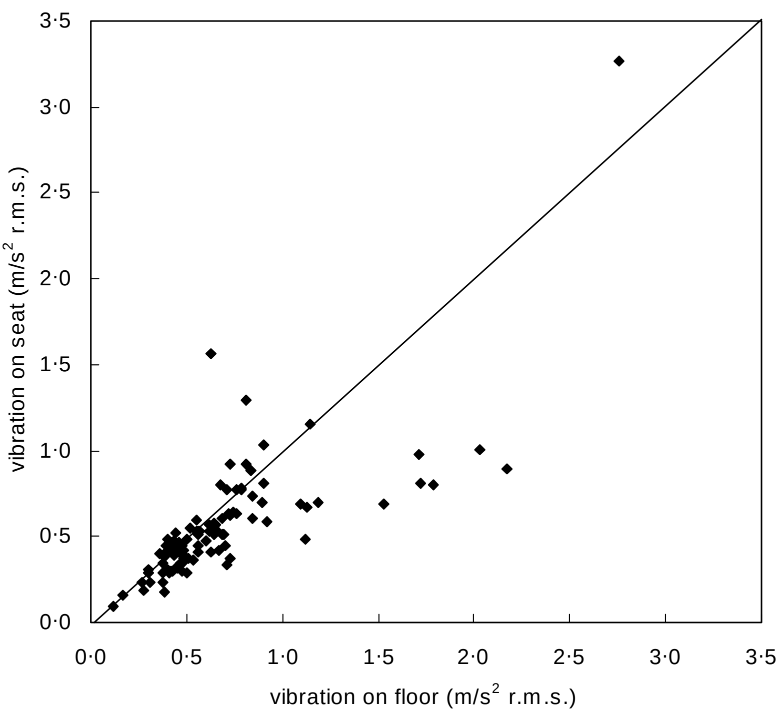

Figure 3. Frequency-weighted vibration magnitudes measured on the floor and the seat for 100 vehicles (weighting W_b).

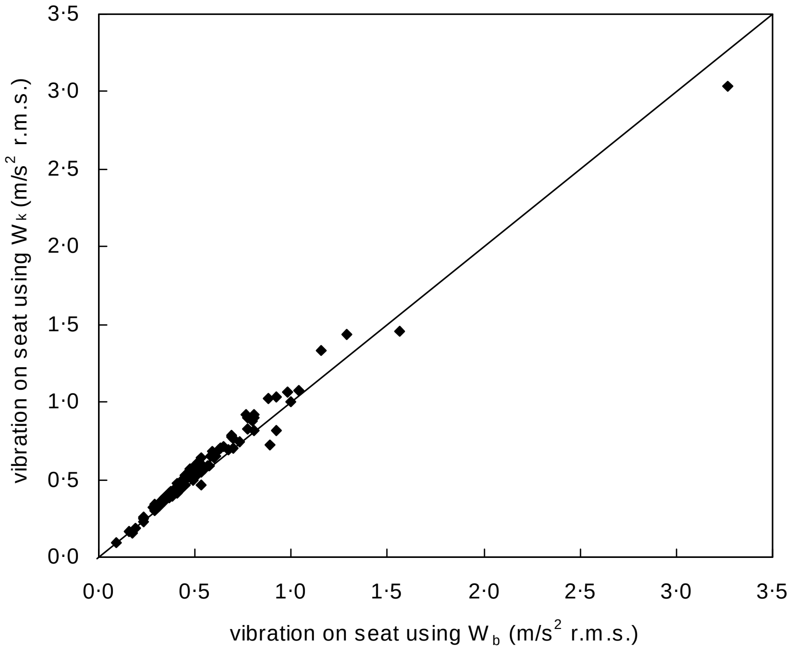

Figure 4. Effect of frequency weighting on vibration measured on the seat for 100 vehicles (weightings W_b and W_k).

TABLE 2

Vibration magnitudes (m/s² r.m.s.) calculated using frequency weighting W_b in vehicles shown by different categories

Category	Number of vehicles measured	Floor vibration Median (range)	Seat vibration Median (range)
Car	25	0·47 (0·16–0·78)	0·36 (0·16–0·78)
Van	9	0·46 (0·40–0·62)	0·43 (0·30–0·57)
Lift truck	11	0·89 (0·46–1·79)	0·69 (0·46–0·92)
Lorry	16	0·70 (0·39–1·12)	0·47 (0·33–1·04)
Tractor	7	0·60 (0·40–1·71)	0·52 (0·29–0·98)
Bus	10	0·48 (0·30–0·74)	0·44 (0·31–0·65)
Dumper	4	0·86 (0·65–1·14)	0·87 (0·54–1·29)
Excavator	4	1·88 (0·12–2·75)	0·91 (0·09–3·27)
Helicopter	1	0·62	1·56
Armoured vehicle	4	0·83 (0·39–2·17)	0·61 (0·17–0·89)
Mobile crane	2	0·54 (0·44–0·64)	0·46 (0·41–0·52)
Grass roller	1	0·72	0·92
Mower	3	0·39 (0·36–0·69)	0·41 (0·40–0·61)
Milk float	3	0·76 (0·73–0·79)	0·78 (0·62–0·79)

An estimate of the efficiencies of the seats in isolating the vibration from the floor for vehicles in different categories can be made by comparing the floor and seat vibration magnitudes as shown in Table 2 and Figure 3 and compared in Figure 5.

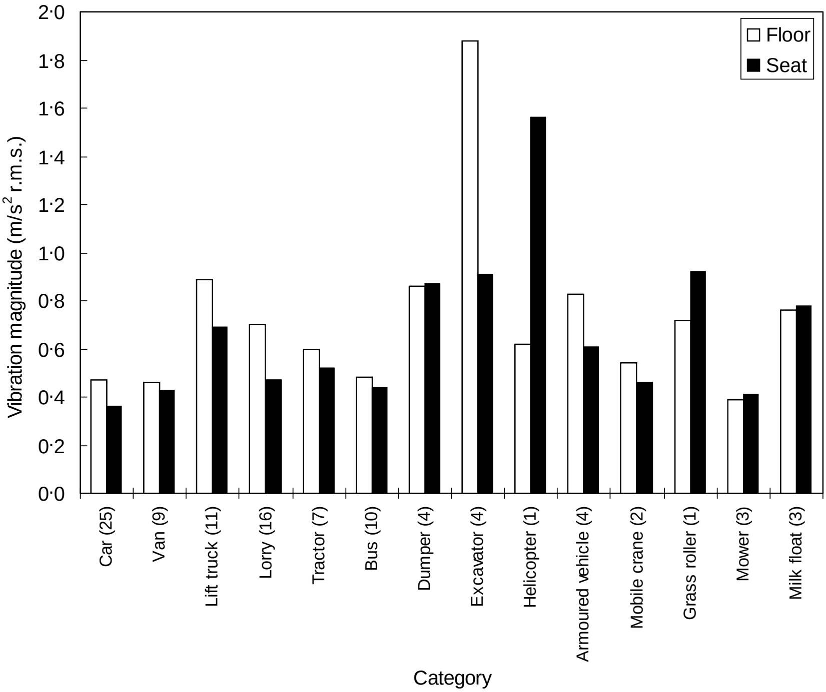

Figure 5. Medians of frequency-weighted vibration magnitudes on the floor and the seat (frequency weighting W_b) measured in 100 vehicles. (Number of vehicles in each category shown in parentheses.)

4.2. MEASURED SEAT VALUES IN VEHICLES

SEAT values were calculated using two frequency weightings (W_b and W_k) and two averaging methods (r.m.s. and VDV). Apart from a few exceptions (for example vehicles 3, 61 and 66), the SEAT values calculated using frequency weighting W_k were slightly greater than those calculated using weighting W_b, for both the r.m.s. and the VDV methods of calculation. The average percentage difference for all vehicles was 6%, for both the r.m.s. and the VDV methods. (SEAT values for all vehicles calculated using the r.m.s. method and frequency weighting W_b are shown in Table 6.)

The effect of the frequency weighting on SEAT values is shown in Figures 6 and 7 for values calculated using r.m.s. averaging and VDV, respectively. The median of all SEAT values shows a higher value when using the W_k weighting (92·5% for the r.m.s. method and 88·2% for the VDV method) compared to when using the W_b weighting (86·8% for the r.m.s. method and 83·0% for the VDV method). This is because frequency-weighting W_k has a higher gain than W_b at low frequencies (see Figure 1) where most vehicles had the most motion and seats cannot provide useful attenuation.

The SEAT values calculated using the r.m.s. and VDV methods are compared in Figures 8 and 9 for frequency weightings W_b and W_k, respectively. For the conditions of the test measurements, the two methods generally gave similar values. One vehicle (vehicle 61, a dumper with a foam seat) gave considerably higher SEAT values with the VDV (159·8% using the r.m.s. method compared to 218·8% calculated using the VDV method with weighting W_b). The crest factors for floor vibration and seat vibration for this vehicle were 5·8 and 10·6 (on the floor and seat, respectively), implying that the seat suspension may have hit its end stops. In these conditions, the VDV method would be expected to provide the

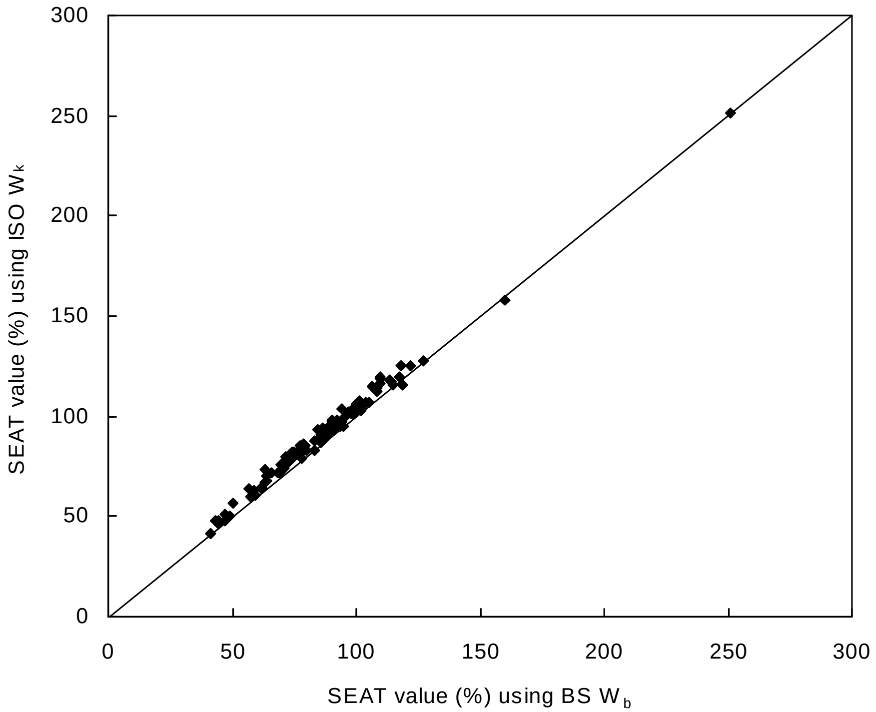

Figure 6. Effect of frequency weighting on $SEAT_{r.m.s.}$ values for 100 vehicles (weightings W_b and W_k).

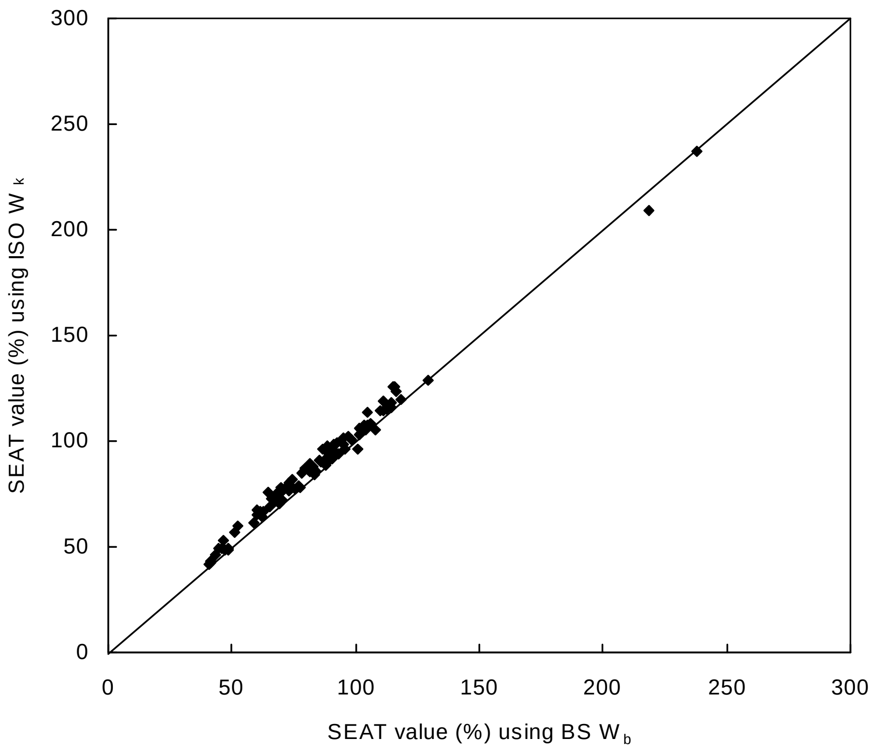

Figure 7. Effect of frequency weighting on $SEAT_{VDV}$ values for 100 vehicles (weightings W_b and W_k).

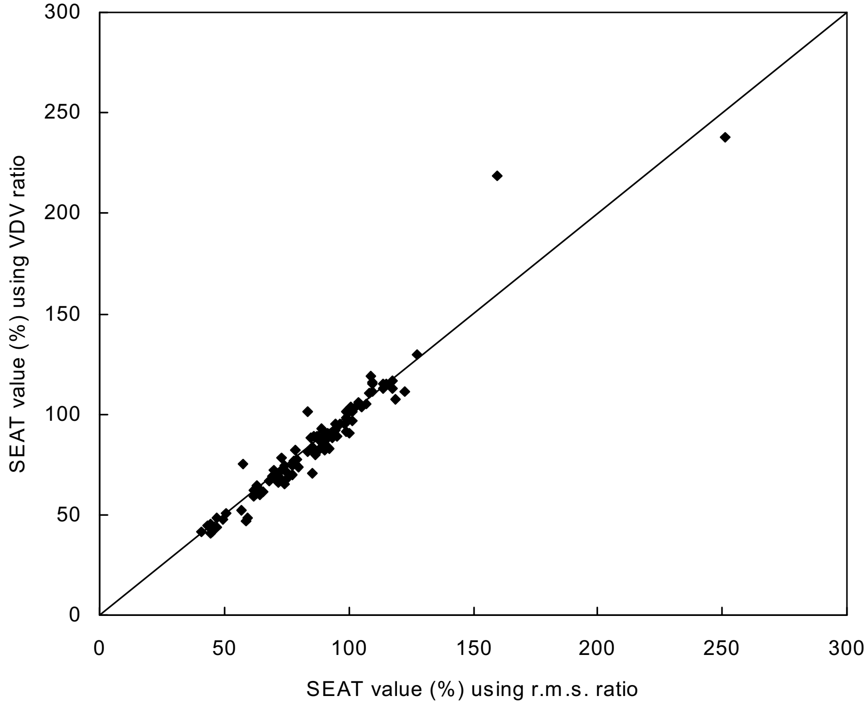

Figure 8. Comparison of r.m.s. and VDV methods on SEAT values for 100 vehicles calculated using weighting W_b.

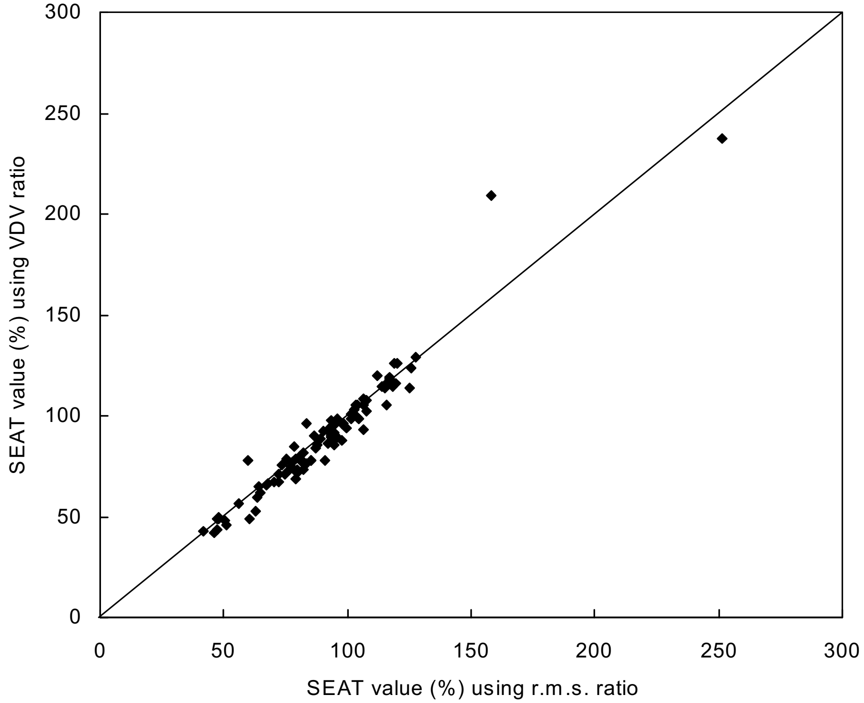

Figure 9. Comparison of r.m.s. and VDV methods on SEAT values for 100 vehicles calculated using weighting W_k.

better estimate of the seat isolation efficiency. For the other measurements, the tests did not include shocks and so both methods appear equally suitable. In general, when conditions are not artificially constrained, the occurrence of shocks is more likely and a greater difference between r.m.s. and VDV methods may be expected. If the shock is present on the floor but is attenuated by the seat suspension, SEAT values calculated from the r.m.s. acceleration will tend to overestimate the SEAT value (i.e., underestimate the attenuation). Conversely, if the shock is introduced by the seat suspension, SEAT values calculated from the r.m.s. acceleration will tend to underestimate the SEAT value. Over the 100 vehicles studied here, the average percentage difference between the $SEAT_{VDV}$ and $SEAT_{r.m.s.}$ values was 4·5% when using frequency weighting W_b (4·6% when excluding vehicle 61).

The average SEAT values for the two categories of seat (conventional seats and suspension seats) are shown in Table 3.

The medians and ranges of SEAT values for the different vehicle categories are summarized in Table 4. It can be seen that there was a wide range of SEAT values within vehicle categories (e.g., for the 11 lift trucks a range from 44·8 to 114·1%).

For vehicle categories having more than four examples, Figure 10 shows the individual and median SEAT values measured in the vehicles (calculated using the r.m.s. method and

TABLE 3

SEAT values (%) for conventional and suspension seats: median (range)

Type of seat	Number of seats	r.m.s. SEAT value (%)		VDV SEAT value (%)	
		W_b (BS 6841)	W_k (ISO 2631)	W_b (BS 6841)	W_k (ISO 2631)
Conventional	67	86·9 (41·1–251·1)	92·6 (41·8–251·2)	83·3 (41·6–238·1)	89·7 (42·7–237·5)
Suspension	33	84·6 (43·5–118·7)	89·2 (46·0–119·9)	82·0 (40·8–118·5)	87·7 (41·8–126·0)

TABLE 4

SEAT values (%) calculated using r.m.s. ratio and frequency weightings W_b and W_k in vehicles shown by different categories

Category	Number of vehicles measured	SEAT value (%) using W_b Median (range)	SEAT value (%) using W_k Median (range)
Car	25	77·6 (56·6–122·2)	82·0 (63·6–125·4)
Van	9	89·7 (71·3–96·7)	94·3 (77·7–102·3)
Lift truck	11	85·6 (44·8–114·1)	87·1 (46·0–117·1)
Lorry	16	86·8 (43·5–115·1)	93·4 (47·6–119·9)
Tractor	7	79·3 (57·2–117·8)	85·0 (60·0–125·5)
Bus	10	89·2 (64·0–117·3)	95·9 (70·5–119·6)
Dumper	4	92·2 (63·3–159·8)	95·4 (67·2–158·3)
Excavator	4	63·3 (47·0–118·7)	67·8 (47·9–115·8)
Helicopter	1	251·1	251·2
Armoured vehicle	4	53·9 (41·1–94·5)	60·9 (41·8–95·1)
Mobile crane	2	86·7 (79·9–93·4)	89·0 (82·7–95·3)
Grass roller	1	127·3	127·5
Mower	3	103·9 (87·9–109·5)	107·3 (93·6–116·7)
Milk float	3	100·0 (85·6–102·0)	102·6 (91·1–103·6)

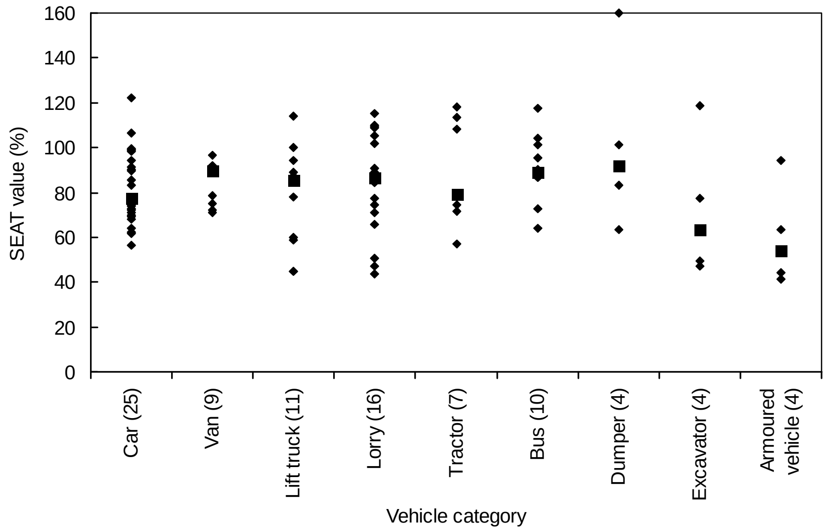

Figure 10. Median (■) and individual (◆) SEAT values measured in vehicles shown by category. (Number of vehicles in each category shown in parentheses; calculated using frequency weighting W_b and r.m.s. values.)

frequency weighting W_b). All vehicle categories in Figure 10 showed median SEAT values less than 100%, although median values greater than 100% were seen for some categories with less than four vehicles (e.g., helicopter, grass roller, mower and milk float).

5. PREDICTION OF SEAT VALUES IN WORK VEHICLES

5.1. INTRODUCTION

It may be possible to estimate the isolation effectiveness (i.e., SEAT value) of a seat from the seat transfer function without measuring the response of the seat in the vehicle. This predictive procedure for assessing seats has been considered elsewhere (e.g., references [2, 10, 11]). A frequency-domain procedure was used to predict SEAT values presented in this paper based on the W_b frequency weighting and r.m.s. averaging.

5.2. SEAT VALUES PREDICTED FOR SEATS INTERCHANGED BETWEEN VEHICLES

The predictions of SEAT values for all combinations of seats and vehicles resulted in a 100×100 matrix. As an example of the data, predicted values for the first 10 vehicles and their seats are shown in Table 5 (i.e., predicted SEAT values if 10 of the seats in 10 of the vehicles were interchanged in all possible combinations). (Seat n was in vehicle n during the measurements; for example, the measured SEAT value for vehicle 1 (i.e., seat 1 in vehicle 1) was 91·2% (see Table 6).) The columns of Table 5 show the predicted effect of putting one seat in 10 different vehicles. For example, if seat 1 was placed in vehicle 5, a SEAT value of 71·8% is predicted; the same seat in vehicle 6 is predicted to give a SEAT value of 120·9%. The rows show the different SEAT values predicted when different seats are placed in the same vehicle. For example, with seat 10 placed in vehicle 1 a SEAT value of 74·7% is predicted, whereas with seat 6 in vehicle 1 a SEAT value of 119·2% is predicted.

TABLE 5

Predicted SEAT values (%) calculated using r.m.s. values and frequency-weighting W_b for the seats in 10 different vehicles

Vehicle	Seat 1	Seat 2	Seat 3	Seat 4	Seat 5	Seat 6	Seat 7	Seat 8	Seat 9	Seat 10
1	**88·8** (82·9–94·8)	**87·2** (76·3–98·3)	81·6 (47·2–132·7)	**80·0** (70·1–90·0)	**65·6** (55·2–76·3)	119·2 (79·9–165·3)	89·0 (68·2–110·8)	54·9 (36·4–94·4)	92·7 (68·9–119·1)	**74·7** (70·0–79·5)
2	**72·6** (66·6–78·8)	**69·6** (61·6–77·9)	63·0 (41·5–92·9)	**63·9** (56·0–72·1)	**54·4** (45·9–63·6)	91·1 (62·7–124·2)	76·0 (61·1–92·2)	42·2 (26·8–70·8)	100·8 (71·1–133·5)	**62·0** (57·4–66·9)
3	**101·0** (92·1–109·9)	**113·3** (98·0–128·8)	55·2 (45·9–67·8)	**118·3** (105·7–130·9)	**101·7** (87·7–115·9)	116·6 (88·4–147·0)	**98·7** (87·7–110·6)	54·8 (39·8–76·3)	**103·5** (84·9–123·2)	**106·8** (98·1–115·7)
4	**85·0** (78·7–91·4)	**76·0** (64·7–87·3)	84·5 (34·5–154·6)	**44·4** (40·7–48·2)	**41·5** (37·1–46·2)	175·3 (115·5–239·1)	75·4 (49·7–102·0)	42·1 (25·9–90·0)	96·0 (75·4–117·4)	**61·0** (57·5–64·5)
5	**71·8** (66·4–77·3)	**62·7** (53·7–71·7)	45·7 (22·1–87·4)	**42·9** (36·4–49·5)	**47·2** (44·4–50·2)	127·6 (78·1–179·6)	56·5 (36·1–78·6)	36·4 (21·0–78·7)	96·7 (74·7–119·7)	**54·4** (52·1–56·7)
6	**120·9** (107·2–134·6)	**146·5** (121·0–172·1)	37·5 (28·1–49·7)	**120·8** (107·3–134·2)	**84·7** (70·0–99·7)	**74·6** (63·0–87·0)	**96·1** (86·1–106·5)	63·2 (41·2–87·0)	**108·2** (92·5–124·2)	**109·1** (96·7–121·6)
7	**109·8** (98·2–121·5)	**133·7** (115·8–151·8)	54·5 (44·1–66·3)	**128·3** (114·6–142·1)	**91·1** (75·3–107·1)	**97·2** (78·5–116·2)	**111·0** (105·7–116·7)	54·4 (40·9–69·0)	**109·3** (94·0–125·3)	**114·8** (104·0–125·8)
8	**89·6** (82·0–97·5)	**91·0** (81·7–100·5)	60·2 (50·7–73·0)	**118·6** (106·3–131·0)	**115·5** (101·4–129·9)	127·3 (97·0–158·8)	**94·3** (80·2–109·5)	53·1 (42·1–65·2)	111·3 (86·9–136·9)	**103·7** (97·2–110·4)
9	**71·9** (65·0–79·1)	**70·0** (59·1–81·1)	65·5 (39·4–103·5)	**52·3** (46·1–59·2)	**39·9** (33·6–46·8)	90·8 (60·2–125·6)	85·1 (68·7–102·7)	37·5 (21·0–69·4)	**107·8** (89·4–128·2)	**56·8** (51·7–62·3)
10	**83·9** (78·1–89·8)	**79·1** (68·6–89·8)	59·6 (35·2–100·0)	**72·0** (63·0–81·1)	**63·2** (55·0–71·7)	123·9 (82·0–170·4)	77·1 (56·8–98·6)	48·7 (32·2–86·4)	94·4 (73·0–116·8)	**69·7** (66·3–73·2)

Lower and upper confidence interval in parentheses. Predicted SEAT values that met the selection criterion are shown in **bold**.

TABLE 6

SEAT values (%) calculated for the seats in 100 different vehicles, showing predictions that met the selection criterion (values in parentheses show number as percentage of "valid" predictions)

Vehicle number	Vehicle type	Measured r.m.s. SEAT value (%)	Number of predictions accepted	Number (%) of predictions < measured SEAT value	Number (%) of predictions <80% of measured SEAT value
1	Car	91·2	73	61(84%)	28(38%)
2	Excavator	77·4	68	56(82%)	21(31%)
3	Dumper	83·4	80	5(6%)	3(4%)
4	Excavator	47·0	68	9(13%)	4(6%)
5	Excavator	49·3	71	17(24%)	6(8%)
6	Lift truck	89·3	81	12(15%)	5(6%)
7	Lift truck	114·1	80	31(39%)	14(18%)
8	Tractor	71·7	80	4(5%)	3(4%)
9	Grass roller	127·3	69	69(100%)	67(97%)
10	Lorry	71·2	72	25(35%)	7(10%)
11	Van	71·3	77	39(51%)	7(9%)
12	Mower	103·9	72	45(63%)	18(25%)
13	Tractor	108·1	80	30(38%)	6(8%)
14	Tractor	79·3	77	9(12%)	1(1%)
15	Tractor	113·5	84	40(48%)	9(11%)
16	Lorry	77·4	74	6(8%)	1(1%)
17	Lorry	90·9	75	25(33%)	7(9%)
18	Van	92·1	71	61(86%)	23(32%)
19	Lift truck	100·1	82	50(61%)	10(12%)
20	Milk float	100·0	79	16(20%)	3(4%)
21	Milk float	85·6	75	11(15%)	1(1%)
22	Milk float	102·0	84	23(27%)	4(5%)
23	Mower	109·5	77	40(52%)	10(13%)
24	Mower	87·9	72	18(25%)	8(11%)
25	Lorry	108·6	83	44(53%)	3(4%)
26	Lift truck	58·7	72	4(6%)	0(0%)
27	Lorry	115·1	73	68(93%)	45(62%)
28	Lift truck	59·7	71	7(10%)	2(3%)
29	Car	90·0	71	55(77%)	23(32%)
30	Car	98·1	73	45(62%)	13(18%)
31	Lorry	65·5	70	20(29%)	7(10%)
32	Van	89·7	72	60(83%)	15(21%)
33	Car	94·2	69	64(93%)	36(52%)
34	Dumper	101·0	83	22(27%)	6(7%)
35	Lorry	105·0	83	43(52%)	1(1%)
36	Lorry	89·0	75	35(47%)	5(7%)
37	Lorry	101·7	81	45(56%)	3(4%)
38	Car	72·0	74	48(65%)	19(26%)
39	Car	74·5	74	44(59%)	8(11%)
40	Car	85·8	76	57(75%)	23(30%)
41	Mobile crane	79·9	71	19(27%)	7(10%)
42	Lorry	46·9	73	7(10%)	0(0%)
43	Lorry	50·5	72	7(10%)	0(0%)
44	Lorry	43·5	73	2(3%)	0(0%)
45	Lorry	109·8	79	53(67%)	7(9%)
46	Lorry	109·6	76	50(66%)	7(9%)
47	Lorry	84·6	77	15(19%)	3(4%)
48	Car	68·3	70	10(14%)	4(6%)
49	Car	69·8	69	40(58%)	15(22%)

TABLE 6
Continued

Vehicle number	Vehicle type	Measured r.m.s. SEAT value (%)	Number of predictions accepted	Number (%) of predictions < measured SEAT value	Number (%) of predictions < 80% of measured SEAT value
50	Mobile crane	93·4	71	50(70%)	21(30%)
51	Car	122·2	71	70(99%)	66(93%)
52	Car	61·8	68	33(49%)	15(22%)
53	Car	69·1	64	42(66%)	20(31%)
54	Car	99·1	71	51(72%)	15(21%)
55	Car	77·6	71	20(28%)	8(11%)
56	Car	62·0	67	17(25%)	6(9%)
57	Car	106·7	63	60(95%)	52(83%)
58	Tractor	57·2	77	1(1%)	1(1%)
59	Car	89·5	73	65(89%)	37(51%)
60	Tractor	117·8	80	36(45%)	14(18%)
61	Dumper	159·8	83	74(89%)	54(65%)
62	Armoured vehicle	63·3	71	12(17%)	1(1%)
63	Armoured vehicle	41·1	32	26(81%)	20(63%)
64	Van	90·4	71	56(79%)	28(39%)
65	Lift truck	94·5	83	22(27%)	4(5%)
66	Excavator	118·7	61	59(97%)	56(92%)
67	Dumper	63·3	78	3(4%)	2(3%)
68	Helicopter	251·1	68	68(100%)	66(97%)
69	Bus	103·9	75	67(89%)	28(37%)
70	Bus	64·0	73	17(23%)	3(4%)
71	Bus	86·6	73	57(78%)	19(26%)
72	Bus	101·5	77	51(66%)	7(9%)
73	Van	72·0	72	25(35%)	7(10%)
74	Van	96·7	72	56(78%)	23(32%)
75	Van	91·7	72	63(88%)	23(32%)
76	Van	75·2	71	42(59%)	18(25%)
77	Car	99·2	69	64(93%)	34(49%)
78	Car	99·0	76	44(58%)	14(18%)
79	Car	70·8	72	42(58%)	8(11%)
80	Car	83·4	76	15(20%)	3(4%)
81	Lift truck	44·8	78	2(3%)	0(0%)
82	Lift truck	45·0	77	1(1%)	0(0%)
83	Lorry	74·7	74	4(5%)	1(1%)
84	Tractor	74·2	74	8(11%)	4(5%)
85	Van	78·6	71	45(63%)	11(15%)
86	Bus	117·3	85	48(56%)	7(8%)
87	Bus	88·1	73	45(62%)	15(21%)
88	Bus	86·9	72	37(51%)	7(10%)
89	Lift truck	87·3	68	37(54%)	11(16%)
90	Lift truck	85·6	70	25(36%)	12(17%)
91	Lift truck	77·9	69	19(28%)	9(13%)
92	Armoured vehicle	44·4	50	35(70%)	19(38%)
93	Armoured vehicle	94·5	56	56(100%)	53(95%)
94	Bus	95·4	73	53(73%)	16(22%)
95	Bus	90·4	76	30(39%)	5(7%)
96	Bus	72·9	74	35(47%)	8(11%)
97	Car	56·6	75	19(25%)	4(5%)
98	Car	73·0	70	49(70%)	22(31%)
99	Car	73·8	72	41(57%)	9(13%)
100	Car	63·7	68	36(53%)	17(25%)

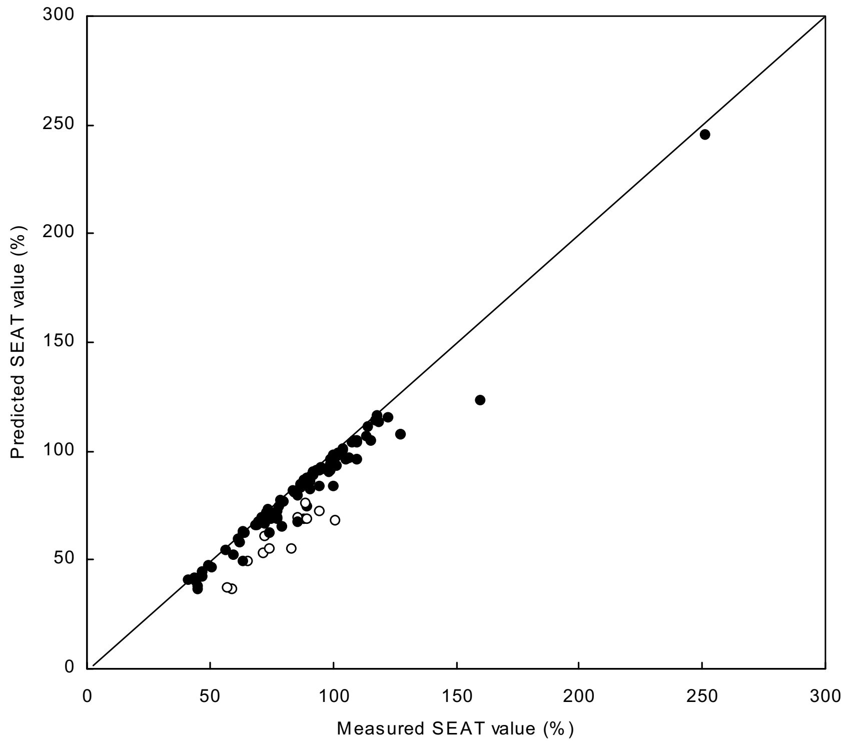

Figure 11. Comparison of measured and predicted $SEAT_{r.m.s.}$ values for 100 vehicles (weighting W_b). (○ circles correspond to data points that failed the acceptability criteria.)

It is seen from the predictions in Table 5 and the measurements in Table 6 that there are differences between the measured and predicted SEAT values for a seat in the vehicle in which it was measured. The results show that predicted SEAT values are lower than the measured SEAT values. This is the case for all vehicles (see Figure 11). It is seen that the difference between the measured and the predicted SEAT values is large for some vehicles. For example, the point in Figure 11 that deviates most from the diagonal corresponds to vehicle 61 (a dumper with a foam seat) where the measured SEAT value was 159·8% and the predicted SEAT value was 123·4%; this corresponds to an "error" of 22·8% of the measured SEAT value. Ratios of the differences between the measured and the predicted SEAT values for the seats in all 100 vehicles are shown in Figure 12. The highest ratio for any of the vehicles was for vehicle 26 (lift truck with a suspension seat) where the measured SEAT value was 58·7% and the predicted SEAT value was 36·8%: the ratio of the difference to the measured SEAT value was 0·37.

Some of the differences between the measured and the predicted SEAT values can be explained in terms of a model of the vibration transmission through seats. The predicted SEAT values are based on a linear relationship between acceleration at the base of the seat and the acceleration measured on the top of the seat; this is illustrated by the transfer function shown in equation (3) (section 3.3). However, there is a "noise" or remnant part of the signal measured on the seat that is not correlated with acceleration at the base of the seat. This can be represented as

$$A_s(f) = A_f(f)H(f) + A_n(f), \tag{10}$$

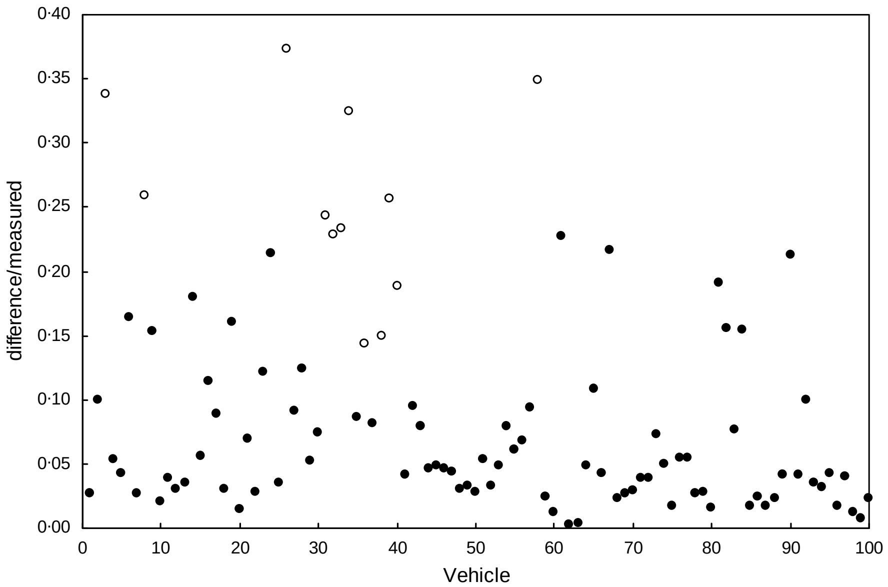

Figure 12. Ratio of difference (between predicted and measured) in SEAT to the measured SEAT values for 100 vehicles. (Calculated using weighting W_b and r.m.s. values. ○ circles correspond to data points that failed the acceptability criteria.)

where $A_s(f)$ is the acceleration on the seat surface (m/s^2), $A_f(f)$ is the acceleration at the seat base (m/s^2), $H(f)$ is the seat transfer function, and $A_n(f)$ is the noise component of the acceleration on the seat surface (m/s^2).

The component of acceleration in the above equation corresponding to noise would include a non-linear remnant due to friction in the seat mechanism for suspension seats, end-stop contacts for suspension seats, driver-generated motions, etc. The power spectral density of the remnant, $A_n(f)$, can be estimated as:

$$G_{nn}(f) \approx G_{ss}(f)(1 - \gamma^2(f)), \tag{11}$$

where $G_{nn}(f)$ is the power spectral density of the noise component of acceleration on the seat surface, $G_{ss}(f)$ is the power spectral density of acceleration on the seat surface, and $\gamma(f)$ is the coherency between acceleration at the seat base and on top of the seat.

The power spectral density represented in equation (11) corresponds to the noise component (or the remnant) and could be included in a refinement of the estimates of the predicted SEAT values. Equation (6) (section 3.5) was used in the calculation of the predicted SEAT values. In light of the estimate of the noise component, equation (6) could be modified to include the noise component:

$$SEAT\ (\%) = \frac{\left[\int\limits_{f=0\cdot 5}^{f=80} (G_{ff}(f)\,|H(f)|^2\,S^2(f) + G_{nn}(f)\,S^2(f))\,\mathrm{d}f\right]^{1/2}}{\left[\int\limits_{f=0\cdot 5}^{f=80} G_{ff}(f)\,S^2(f)\,\mathrm{d}f\right]^{1/2}} \times 100\%. \tag{12}$$

Equation (12) would be expected to provide a better estimate of the predicted SEAT values, and thus a better correlation between the predicted and measured SEAT values than those shown in Figure 11 (calculated using equation (6)).

Lower and upper SEAT values, corresponding to the 95% confidence intervals, were estimated for all vehicles (see section 3.5 for method of calculation based on coherency). Estimated lower and upper SEAT values for the first 10 vehicles are also shown in Table 5. The range of the SEAT values, between the lower and the upper confidence intervals, is dependent on the coherency between the floor and the seat vibration. Coherencies for all vehicles have been presented elsewhere [12].

An example of the range between the lower and the upper confidence intervals can be considered for seat 10 placed in vehicle 1: the estimated mean SEAT value is 74·7% with a 95% confidence interval from 70·0 to 79·5% (see Table 5). In this case, the 95% confidence interval for the SEAT values corresponds to about 6% of the mean SEAT value. There are other combinations of seats and vehicles where the difference is much greater. For example, seat 3 placed in vehicle 1 shows a mean SEAT value of 81·6% with lower and upper values of 47·2 and 132·7%. This corresponds to a range of about 62% of the estimated mean SEAT value.

A criterion for accepting and rejecting SEAT values based on the confidence that could be placed on the estimated mean value was defined. Estimated mean SEAT values were accepted if the SEAT values calculated from the transmissibilities at the 95% confidence interval fell within $\pm 20\%$ of the estimated mean SEAT value. So, the predicted SEAT values were accepted when both the following criteria were satisfied:

$$\text{lower SEAT value} > 0{\cdot}8 \text{ of mean predicted SEAT value}$$

$$\text{upper SEAT value} < 1{\cdot}2 \text{ of mean predicted SEAT value.}$$

Otherwise, the predictions were rejected as being inaccurate.

Table 5 shows, in bold, those estimated mean SEAT values that satisfy the selection criteria. Estimated SEAT values that are not shown in bold correspond to values with "unacceptable" confidence intervals. For the combination of 10 seats and 10 vehicles, predictions using seats 3 and 8 are not acceptable for any of the 10 vehicles. The selection criteria were such that predictions could be made for seats 1, 2, 4, 5 and 10 with all of the first 10 vehicles. A large variation in predicted SEAT values is seen for some vehicles. For example, vehicle 9, a grass roller has estimated SEAT values varying from 39·9 to 107·8%, depending on which seat is fitted. The highest value (i.e., the worst) was with the seat currently fitted to the vehicle.

Using the above criteria for accepting the predicted mean SEAT value if the lower confidence interval is greater than 0·8 of the mean and if the upper confidence interval is less than 1·2 of the mean, it is possible to revisit the accuracy of the predictions. The accuracy of predicted SEAT values for seats in their own vehicles is shown in Figures 11 and 12. A total of 12 of the 100 seats failed the criterion for accepting a predicted SEAT value determined for the seat in its own vehicle; these 12 seats are shown in Figures 11 and 12 as hollow circles. These figures show that the seat–vehicle combinations that had the greatest percentage errors in the predictions tended to fail the criteria.

A table similar to Table 5 showing acceptable estimated mean SEAT values for the 100 seats and vehicles was calculated. It showed that seats 3 (a suspension seat from a dumper), 8 (a suspension seat from a tractor), 26 (a suspension seat from a lift truck) and 39 (a foam seat from a car) could not be used to estimate the SEAT value in any vehicle. For these seats, the confidence intervals were too wide at all significant frequencies in the floor spectra of the 100 vehicles.

Table 6 shows, for each vehicle, the measured SEAT value, the number of accepted predictions of SEAT values using other seats, the number of predicted SEAT values that were below the measured SEAT value and the number of predicted SEAT values that were less than 80% of the measured SEAT value. For some vehicles, the measured SEAT values were higher than all predicted SEAT values using alternative seats. This implies that using any of the other seats would result in a lower SEAT value. This is the case for vehicle 93 (an armoured vehicle) where the measured SEAT value was 94·5% and the predicted SEAT values ranged from 29·5 to 93·7%. There were some vehicles for which only one seat was predicted to result in a SEAT value lower than the measured SEAT value. For example, although there were 77 seats with acceptable predictions of SEAT values for vehicle 58 (a tractor), only 1 seat (seat 82, a suspension seat from a lift truck) gave a lower predicted value than the measured SEAT value.

It may be seen in Table 6 that there were six vehicles (26, 42, 43, 44, 81 and 82) that would not benefit from having a seat from a different vehicle. These vehicles have a zero in the column entitled "*Number* (%) *of predictions* < 80% *of measured SEAT value*". It therefore appears that, of the 100 vehicles included in the study, 94% could benefit from having a seat with the dynamic properties of a seat from another vehicle.

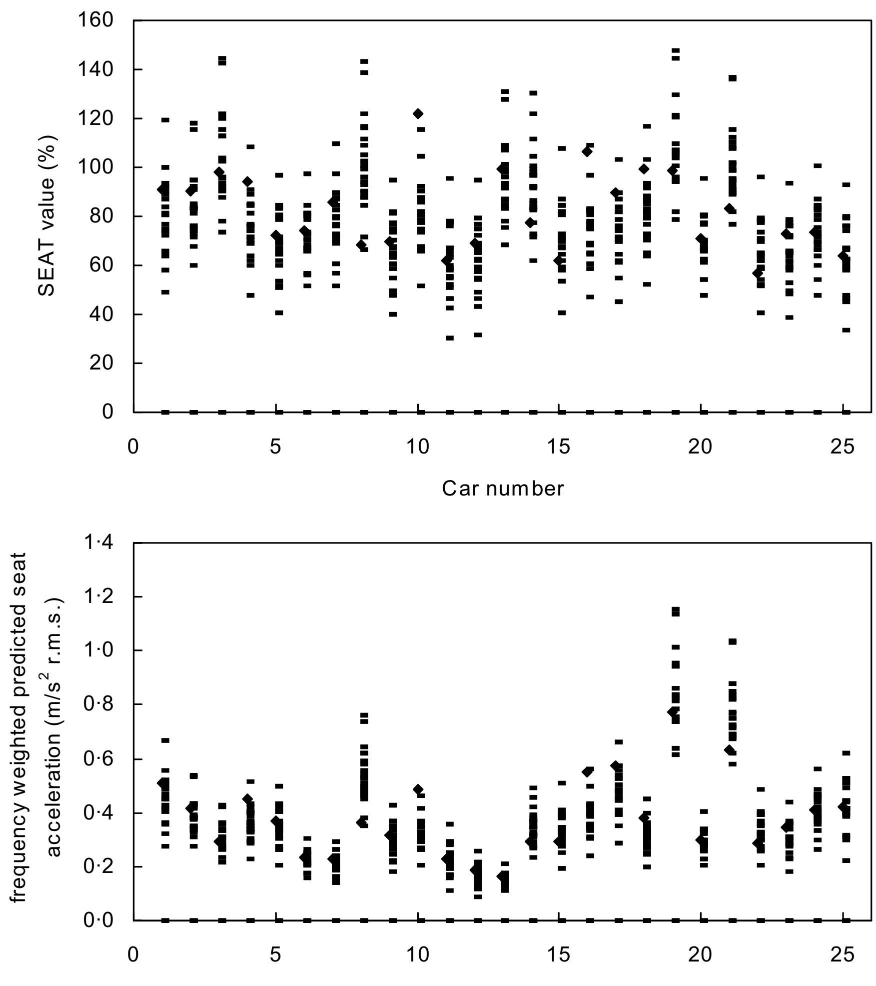

Figure 13. Measured (◆◆◆) and predicted (■ ■) SEAT values and seat acceleration magnitudes for 25 cars. (Calculated using weighting W_b and r.m.s. values.)

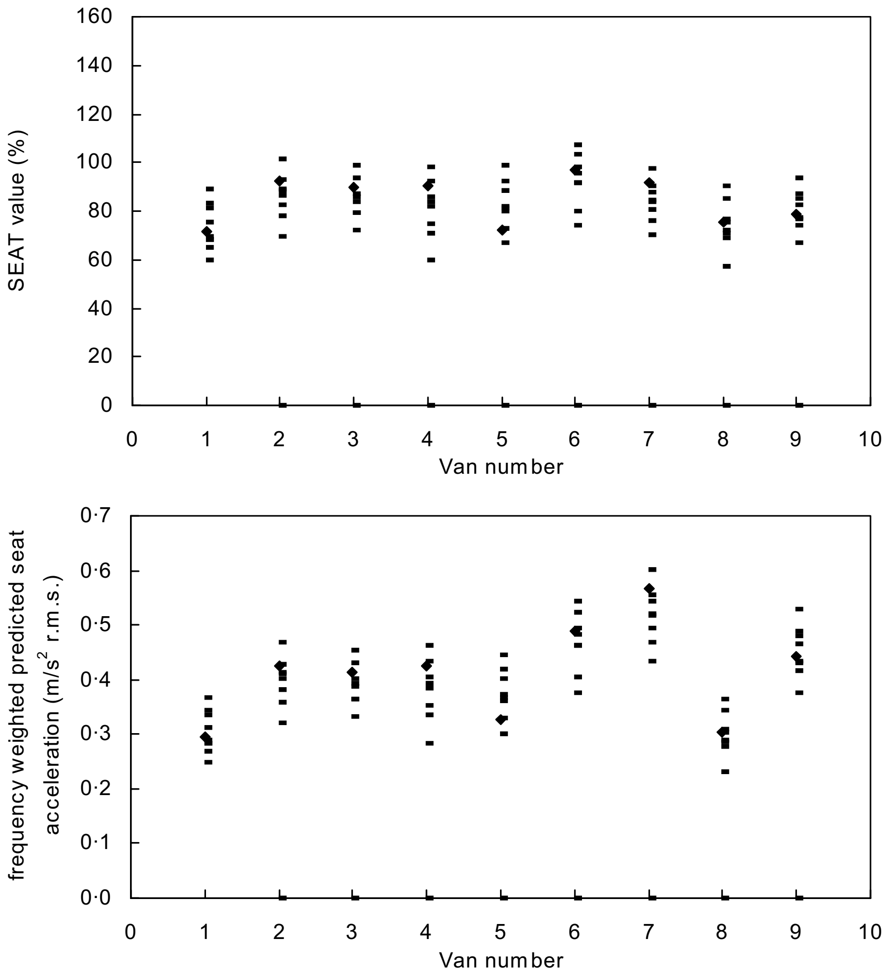

Figure 14. Measured (◆◆◆) and predicted (■ ■) SEAT values and seat acceleration magnitudes for nine vans. (Calculated using weighting W_b and r.m.s. values.)

The range of predicted SEAT values for the 25 cars used in the study is compared to the measured SEAT values in Figure 13.

To predict the effect of exchanging seats between vehicles, the acceleration predicted to occur on the seat was calculated for each seat–vehicle combination. The predicted acceleration magnitudes for the 25 cars are shown in Figure 13 together with the predicted SEAT values. Only the data that fulfilled the above criteria are shown in Figure 13. The measured SEAT values and measured frequency-weighted vibration magnitudes on the seats are shown as diamonds; predicted SEAT values and predicted frequency-weighted vibration magnitudes are shown as rectangles. It is seen, for example, that exchanging the seat in car 10 with a seat having the dynamic response of a seat from any other car would be expected to reduce the SEAT value below the measured value of 122%.

Predicted SEAT values and predicted frequency-weighted accelerations were calculated for vehicles in five other categories (nine vans, 11 lift trucks, 16 lorries, seven tractors and 10 buses), as shown in Figures 14, 15, 16, 17 and 18, respectively.

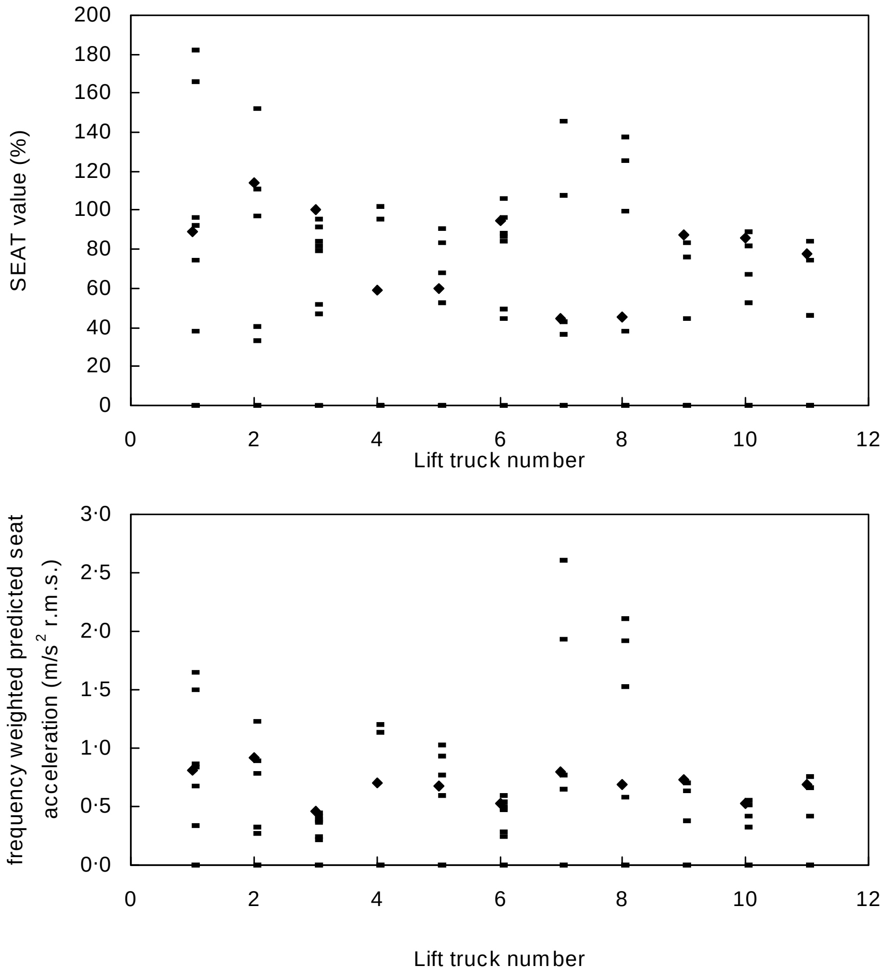

Figure 15. Measured (◆◆◆) and predicted (■ ■) SEAT values and seat acceleration magnitudes for 11 lift trucks. (Calculated using weighting W_b and r.m.s. values.)

6. DISCUSSION AND CONCLUSIONS

Measurements of seat isolation efficiencies showed that 75 out of 100 vehicles had SEAT values less than 100%. However, there was a large variation in SEAT values within categories of vehicle. Since vehicles within a vehicle category tend to have broadly similar vibration spectra [6], this suggests that improvements in ride might be achieved by swapping seats between vehicles.

Apart from a few exceptions, the SEAT values calculated using frequency weighting W_k (from ISO 2631, 1997) were slightly greater than those calculated using weighting W_b (from BS 6841, 1987) for both the r.m.s. and the VDV methods of calculation. The average percentage difference for all vehicles was only 6%, for both the r.m.s. and the VDV methods of calculation.

SEAT values were predicted for seats interchanged between the vehicles. The predictions suggested that 94 vehicles out of the 100 vehicles might benefit from changing to a seat having the dynamic performance of that in one of the other vehicles. It is shown that by

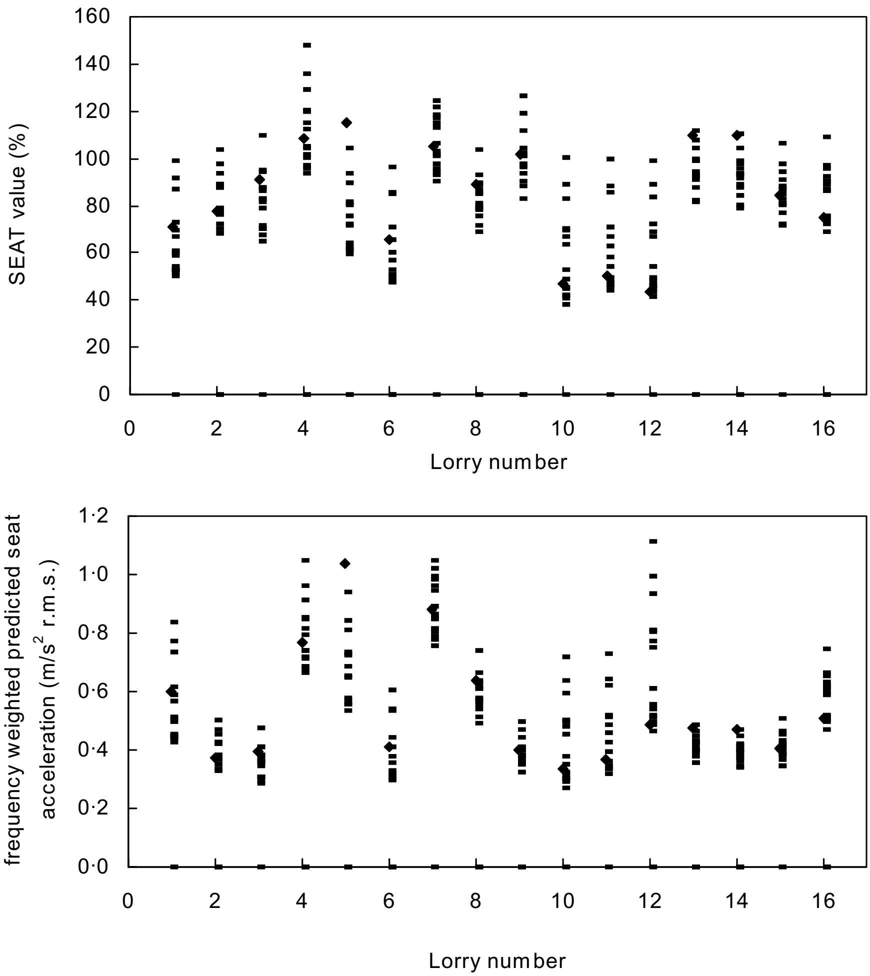

Figure 16. Measured (◆◆◆) and predicted (■ ■) SEAT values and seat acceleration magnitudes for 16 lorries. (Calculated using weighting W_b and r.m.s. values.)

making such changes some significant reductions in exposures to whole-body vibration may be achieved. Although some such changes may not be practical, it would be misleading to thereby imply that significant reductions in exposure cannot be obtained by improvements to seating dynamics. The predictions of SEAT values presented in this paper are based on assumptions that could not be thoroughly tested in this study; future studies may explore the limits to such prediction methods using both laboratory and field data. Some methods of improving the predictions have been suggested.

It may be expected that different methods of prediction and different assumptions may be required with suspension seats (which are inherently highly non-linear at low and high vibration magnitudes). It might even be suggested that for such seats it is not possible to predict their vibration isolation in field conditions. However, if such seats are to be optimized for specific vehicles it is necessary to make such predictions. Current standardized tests for suspension seats involve laboratory simulations of idealized motions representing the typical motions assumed for specific vehicles; some of the limitations of this study also apply to the interpretation of the results of such tests.

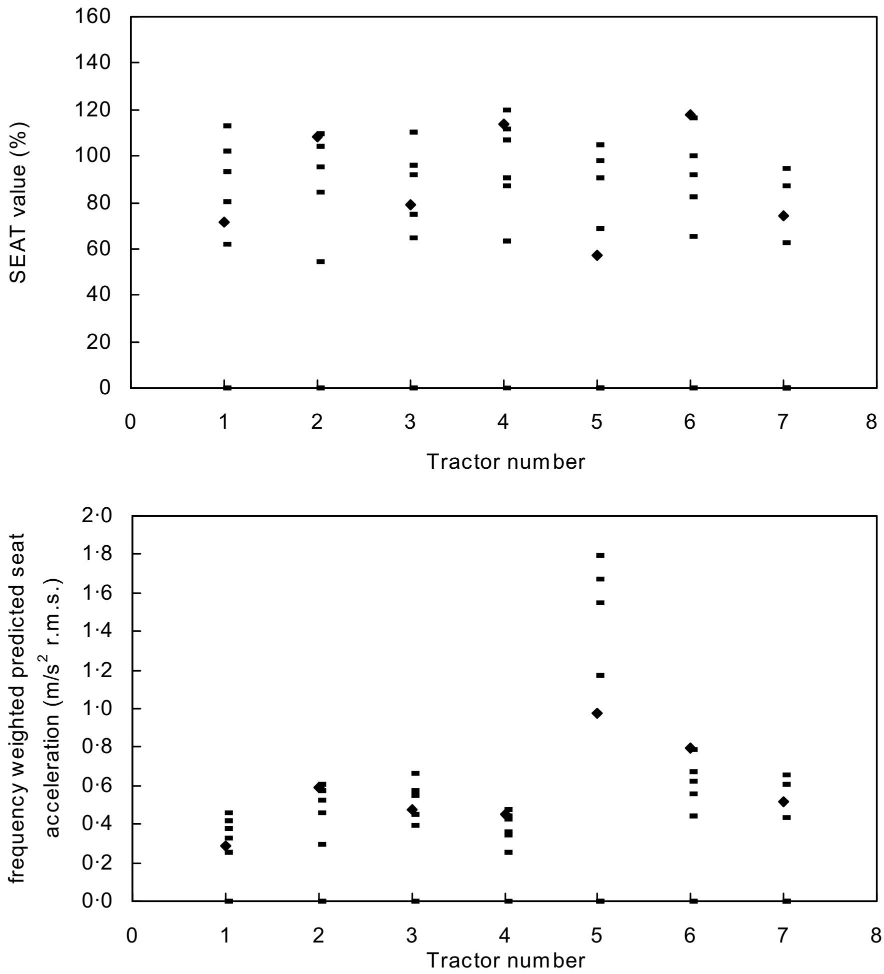

Figure 17. Measured (◆◆◆) and predicted (■ ■) SEAT values and seat acceleration magnitudes for seven tractors. (Calculated using weighting W_b and r.m.s. values.)

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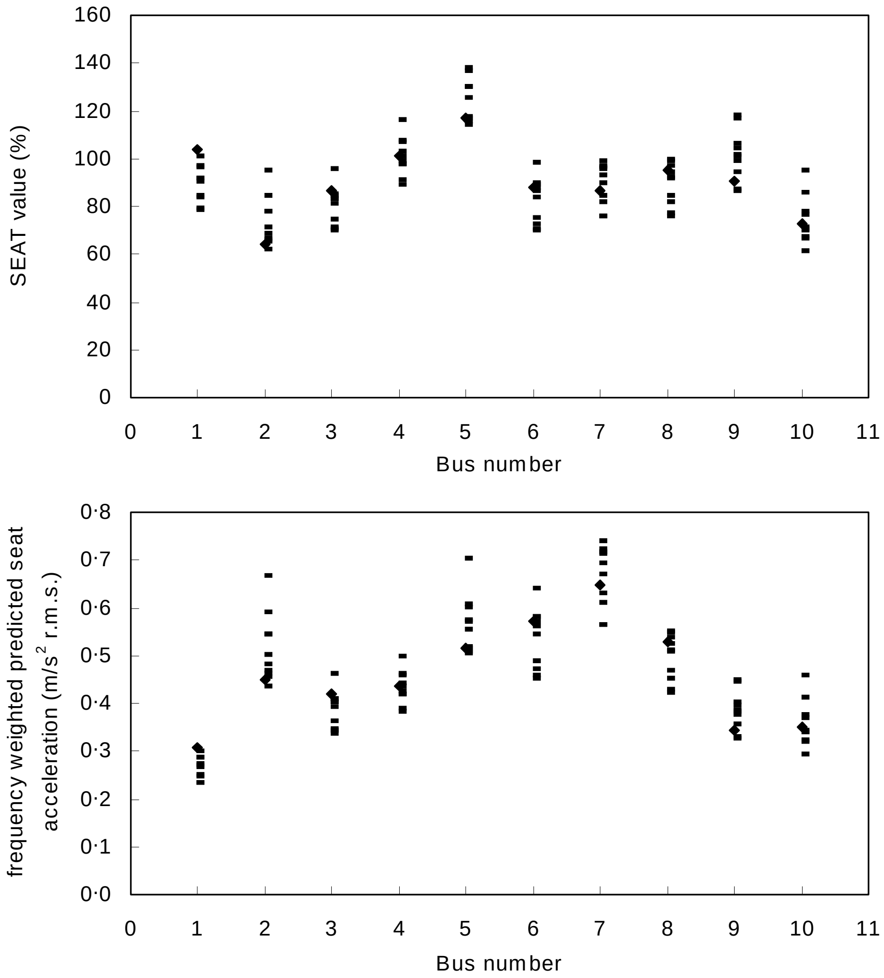

Figure 18. Measured (◆◆◆) and predicted (■ ■) SEAT values and seat acceleration magnitudes for 10 buses. (Calculated using weighting W_b and r.m.s. values.)

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APPENDIX A

This appendix identifies the 100 vehicles in which measurements were made and the operating conditions for each vehicle.

TABLE A1

Descriptions of the vehicles and driving conditions

Vehicle No.	Category	Type of seat	Speed (km/h)	Terrain
1	Car	Foam	Variable	Tarmac
2	Excavator	Foam	Variable	Digging soil
3	Dumper	Suspension	Variable	Mud, soil
4	Excavator	Foam	4	Tarmac
5	Excavator	Suspension	4	Tarmac
6	Lift truck	Foam	Variable	Tarmac
7	Lift truck	Foam	Variable	Tarmac
8	Tractor	Suspension	8	Grass
9	Grass roller	metal "bucket"	Variable	Grass
10	Lorry	Foam, spring	48	Tarmac
11	Van	Foam	112	Tarmac
12	Mower	Foam, leaf	Variable	Tarmac
13	Tractor	Foam	Variable	Tarmac
14	Tractor	Suspension	28	Grass
15	Tractor	Suspension	Mowing	Grass
16	Lorry	Suspension	64	Tarmac, concrete
17	Lorry	Suspension	64	Tarmac, concrete
18	Van	Foam, spring	Variable	Tarmac
19	Lift truck	Suspension	Variable	Concrete
20	Milk float	Foam	Variable	Tarmac, concrete
21	Milk float	Foam	Variable	Tarmac, concrete
22	Milk float	Foam	Variable	Tarmac
23	Mower	Suspension	Mowing	Grass
24	Mower	Suspension	Mowing	Grass
25	Lorry	Suspension	Variable	Tarmac
26	Lift truck	Suspension	Variable	Tarmac
27	Lorry	Suspension	Variable	Tarmac
28	Lift truck	Foam	Variable	Tarmac, concrete
29	Car	Foam	Variable	Tarmac
30	Car	Foam	Variable	Tarmac
31	Lorry	Foam, spring	Variable	Tarmac
32	Van	Foam, spring	Variable	Tarmac
33	Car	Foam, spring	Variable	Tarmac
34	Dumper	Foam	Variable	Mud, soil
35	Lorry	Foam, spring	Variable	Gravel, soil
36	Lorry	Foam	48–64	Tarmac
37	Lorry	Foam	48	Tarmac
38	Car	Foam	113	Tarmac
39	Car	Foam	113	Tarmac
40	Car	Foam	113	Tarmac
41	Mobile crane	Suspension	26	Concrete, paving
42	Lorry	Suspension	Variable	Tarmac
43	Lorry	Suspension	64	Tarmac
44	Lorry	Suspension	80	Concrete
45	Lorry	Suspension	80	Concrete
46	Lorry	Suspension	80	Concrete
47	Lorry	Suspension	64	Tarmac
48	Car	Foam	48	Tarmac

TABLE A1

Continued

Vehicle No.	Category	Type of seat	Speed (km/h)	Terrain
49	Car	Foam	100	concrete
50	Mobile crane	Suspension	17–19	Tarmac, concrete
51	Car	Foam	24	Tarmac
52	Car	Foam	96	Tarmac
53	Car	Foam	80	Tarmac
54	Car	Foam	16	Tarmac
55	Car	Foam	32	Tarmac
56	Car	Foam	32	Tarmac
57	Car	Foam	48	Tarmac
58	Tractor	Suspension	Variable	Tarmac
59	Car	Foam	112	Concrete
60	Tractor	Foam	Variable	Tarmac
61	Dumper	Foam	Variable	Tarmac
62	Armoured vehicle	Foam	20	Cross-country
63	Armoured vehicle	Foam	28	Concrete
64	Van	Foam	64	Tarmac
65	Lift truck	Suspension	Variable	Tarmac
66	Excavator	Suspension	Variable	Dirt track
67	Dumper	Suspension	Variable	Tarmac
68	Helicopter	Foam	Variable	Flying
69	Bus	Suspension	64	Tarmac
70	Bus	Foam, spring	80	Tarmac
71	Bus	Foam, spring	48–80	Tarmac
72	Bus	Foam	Variable	Tarmac
73	Van	Foam	> 48	Tarmac
74	Van	Foam	48	Tarmac
75	Van	Foam	64	Tarmac
76	Van	Foam	Variable	Tarmac
77	Car	Foam	Variable	Tarmac
78	Car	Foam	48	Tarmac
79	Car	Foam	96	Tarmac
80	Car	Foam	48	Tarmac
81	Lift truck	Suspension	Variable	Concrete
82	Lift truck	Suspension	Variable	Concrete
83	Lorry	Suspension	Variable	Concrete
84	Tractor	Suspension	Variable	Uneven Tarmac
85	Van	Foam, spring	88	Tarmac
86	Bus	Foam	Variable	Concrete
87	Bus	Suspension	Variable	Tarmac
88	Bus	Foam, spring	Variable	Tarmac
89	Lift truck	Suspension	Variable	Tarmac
90	Lift truck	Foam	Variable	Tarmac
91	Lift truck	Foam, pivoted	Variable	Tarmac
92	Armoured vehicle	Foam	20	Gravel
93	Armoured vehicle	Foam	20	Gravel
94	Bus	Foam	Variable	Tarmac
95	Bus	Suspension	Variable	Tarmac
96	Bus	Foam, spring	96	Tarmac
97	Car	Foam	113	Tarmac
98	Car	Foam	113	Concrete
99	Car	Foam	113	Concrete
100	Car	Foam	113	Concrete