EFFECT OF INCREASING MEASUREMENT DURATION ON ‘ACCURACY’ OF WHOLE-BODY VIBRATION FIELD MEASUREMENTS

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Abstract

When searching the literature, one is hard pressed to find reports of whole-body vibration measurements with a duration longer than a few minutes. When making a risk assessment according to standards and directives, the vibration exposure must be assessed and often measured. It has previously been assumed that a measurement of a few minutes will suffice as being representative of the full working day, although there little evidence to back-up this assumption. This paper presents measures of vibration exposure for drivers that were made for a full working day. Using a simple model, the exposures were analysed to investigate the potential errors from making measurements from 10 seconds to 60 minutes when compared with the full working day exposure. It is recommended that measurements of vertical whole-body vibration in vehicles should last at least 10 minutes.

1. Introduction

There is no consistent message in standards regarding the required, or desired, sample time for making whole-body vibration measurements. BS6841 (1987) specifies the shortest time, being 60 seconds for vibration exposures with low crest factors. Proposed European Standard prEN14253 (2003) states that “Where the daily work consists of long uninterrupted operations, a series of sample measurements, each of at least 3 min duration, should be taken at different times of the day…”. For frequency analyses with a one-third octave bandwidth, ISO 2631-1 (1997) specifies that a measurement period of 227 seconds is required to reliably measure vibration at 0.5 Hz and that “The measurement period is normally much longer…”. These recommendations are based on signal processing requirements rather than the nature of whole-body vibration in vehicles.

Vibration signals can be classified in a variety of ways (Griffin, 1990) including those that are deterministic (i.e. the waveform can be exactly predicted) and those that are random (i.e. the waveform cannot be exactly predicted). Random signals can be sub-divided into those that are stationary (i.e. where the statistical properties of the signal do not change with time) and those that are non-stationary (i.e. where the statistical properties of the signal change with time). Vibration field measurements for risk assessments always assume that the vibration is nominally stationary, such that the sample measurement is representative of times when the vibration is not being measured. However, this assumption has not been verified in all vehicles. Indeed, vibration characteristics change according to a complex set of variables depending on the vehicle (e.g. task, speed, driver weight, driving style, road surface, season, weather conditions, etc.) such that some compromises are inevitable when making pragmatic decisions regarding how long to measure.

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It is rare to find reports of vibration exposures that are longer than a few minutes. Many large surveys have used short measurement times and the generalised applicability of these measurements depends on the skill of the investigator in choosing the correct start time and the ideal task to measure (e.g. Paddan et al., 1999). Many such surveys use measurement durations of less than those recommended in ISO2631-1 or prEN14253.

With the imminent introduction of the EU Physical Agents (Vibration) Directive (2002), many millions of assessments and many thousands of measurements will be required. For example, in the UK, the Health and Safety Executive (HSE) estimate that vibration assessments will be undertaken for 1 in 20 of the one million workers exposed to vibration above 0.5 ms^{-2} r.m.s., amounting to 50,000 whole-body vibration assessments (Coles, 2002). The volume of vibration measurements being made across Europe will considerably increase. However, the majority of those making the measurements will be inexperienced and will not necessarily have the expertise to select the most appropriate time to make the vibration measurement. In addition, some operations require measurements to be made autonomously, as it is impossible or impractical for the investigator to travel with the vehicle that is being assessed for whole-body vibration exposure. It would therefore be beneficial to have an evidence based approach to guidance regarding the ideal time to measure the vibration exposure for field measurements.

This paper reports results from a study that investigated long term exposures to whole-body vibration in vehicles and investigated the sensitivity of the reported vibration magnitude to the measurement time.

2. Methods

Long term vibration exposures were measured for the operators of 20 vehicles. The vehicles consisted of three buses, a car, two dumpers, three fire appliances, one fork-lift truck, four heavy goods vehicles (trucks), a land rover, two loaders, a tractor and two vans. Each measurement lasted for the operator's full working shift. However, many vehicles were not driven for the entire duration of the working shift, in which case the operator's daily exposure was measured for those times that driving (or vibration exposure) occurred. For example, although measurements of the fire appliances continued throughout the full working day, many parts of the day did not involve any movement of the appliances and so vibration did not occur during these times. In some cases, the exposure times might have been slightly reduced when compared to a normal day due to the need to take time to explain the experiment to the operators.

For the purposes of this study, the 'unfiltered' vibration exposure time refers to the time from the operator's first exposure to whole-body vibration at work to their last exposure to whole-body vibration at work. If the operation included breaks and times when the machine was stopped, these nominally zero measurements were removed from the data to produce the 'filtered' vibration exposure time. In some cases, vibration was measured on the vehicles during these times due to maintenance

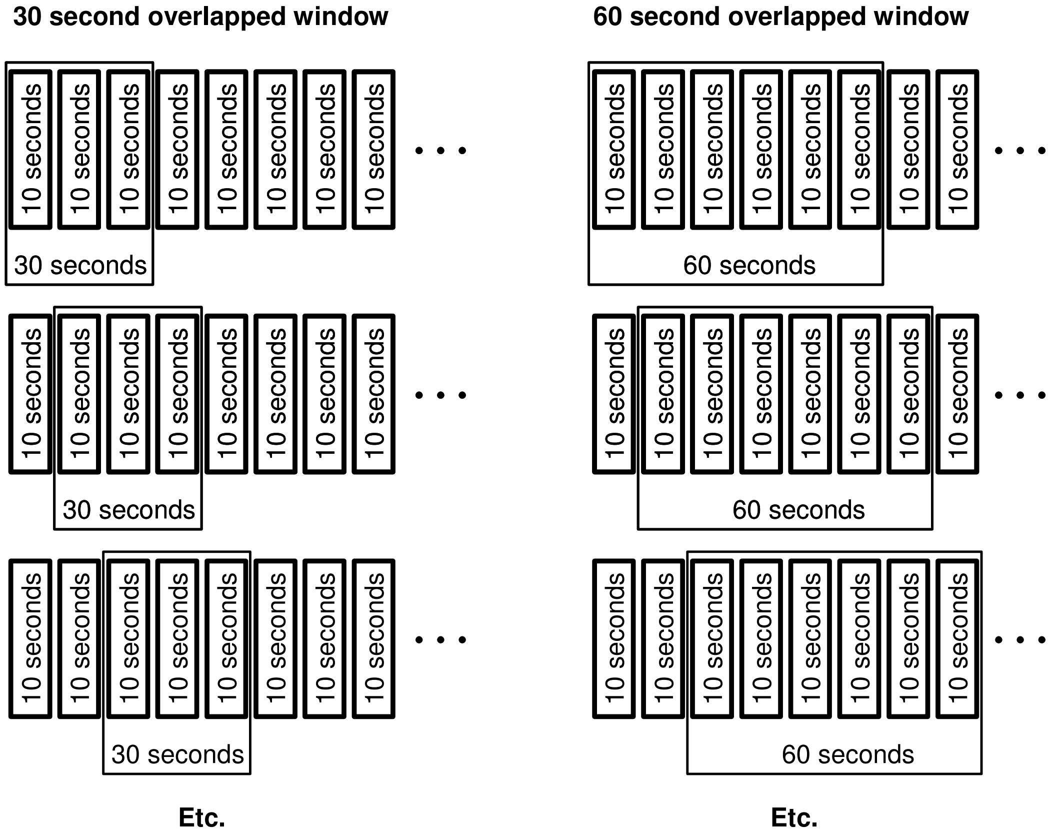

Figure 1. Illustration of the overlapping moving r.m.s. averaging window for 30 and 60 second epochs. Longer windows were also used for 10 minute, 30 minute and 60 minute epochs.

operations. These are not 'true' human vibration exposures and therefore should not be included in a risk assessment and were therefore filtered out (Atkinson et al. 2002).

Two PCB 356M86 triaxial ICP accelerometers were fitted to the vehicles. One was mounted in a standard flexible disc and fixed to the surface of the seat on which the driver sat. The second was mounted on the floor beneath the seat. The accelerometers were attached to two Larson Davis HVM100 vibration meters. These meters frequency weighted the signals and logged the r.m.s. vibration each 10 seconds for the full working shift. Frequency weighting Wd was used for horizontal vibration and frequency weighting Wk was used for vertical vibration. Signals were also conditioned and band limited using the HVM100 meters and these signals were acquired to a stand alone data logger at 256 samples per second for the full shift. This paper only considers the vertical vibration measurements made by the HVM100 for the accelerometer on the surface of the seats, although this was not necessarily the worst axis of vibration for all vehicles.

Data was analysed by combining 10 second vibration measurements into longer time epochs to simulate the effect of increasing measurement time, starting at any arbitrary point during the day. The 10 second measurements of vibration were combined using an overlapping moving r.m.s. average with a window of 30 seconds, 60 seconds, 3 minutes, 10 minutes, 30 minutes and 60 minutes (Figure 1). The step size for the averaging was 10 seconds for all conditions. Therefore, the relative size of the overlap decreases as the averaging epoch increases. As the averaging time increases, the vibration profile is smoothed. Therefore measurements made during any arbitrary time epoch are likely to be closer to the 'true' daily r.m.s. value. Measurements were also combined to give a 'true' full working day vibration exposure.

3. Results

3.1. Full day and filtered results

Vibration exposures measured for the operators of the 20 vehicles are summarised in Table 1. Unfiltered data show that many operators worked for longer than 8 hours between when they were first exposed to vibration and when they stopped being exposed to vibration. However, all operators showed periods of time when there was no vibration exposure. Therefore, the time for the filtered data was reduced substantially for all vehicles. The greatest reduction in exposure time for the filtered data occurred for the vans (less than 20% of the working day involved exposure to vibration); the least reduction for one of the buses, one of the HGVs and one of the loaders (approximately 80% of the time measured involved exposure to vibration). The bus drivers were exposed to the longest periods of vibration during the working day, with two of the operators exceeding 5 hours vibration exposure.

Table 1. Vibration magnitudes and exposure times for whole-body vibration exposures of drivers of 20 different vehicles. Vibration magnitudes are reported as vertical vibration frequency weighted using the Wk frequency weighting.

vehicle	time unfiltered (minutes)	time filtered (minutes)	acceleration unfiltered (m/s^2 r.m.s.)	acceleration filtered (m/s^2 r.m.s.)
bus	289	187	0.31	0.38
bus	516	314	0.40	0.48
bus	420	330	0.52	0.56
car	639	294	0.25	0.36
dumper truck	412	265	0.50	0.63
dumper truck	505	169	0.38	0.63
fire appliance	284	76	0.21	0.40
fire appliance	342	73	0.26	0.56
fire appliance	248	72	0.41	0.85
fork lift truck	162	88	0.69	0.92
HGV	163	128	0.37	0.41
HGV	492	284	0.32	0.40
HGV	495	286	0.46	0.44
HGV	502	262	0.36	0.50
land rover	220	131	0.31	0.39
loader	387	308	0.67	0.75
loader	323	82	0.23	0.45
tractor	384	161	0.24	0.37
van	519	88	0.21	0.50
van	513	98	0.20	0.46

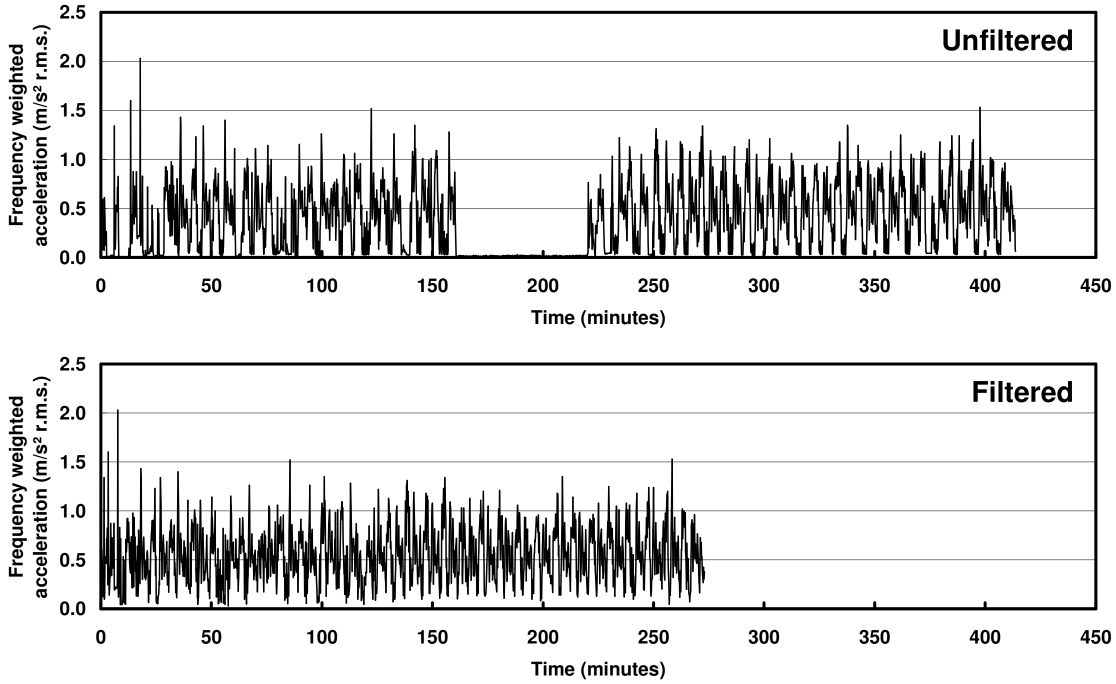

Figure 2. Vertical vibration measured on the seat of a dumper truck with a measurement epoch of 10 seconds. Effect of filtering for periods of zero vibration that correspond to when the vehicle was stopped.

The effect of filtering data is illustrated in Figure 2. In the unfiltered data clear breaks can be observed, the most clear of which is the lunch break. Other shorter periods of no vibration are also removed through the filtering process. Similar characteristics were observed for other vehicles. In the filtered data, these breaks are removed. This effectively simulates an investigator ensuring that a vibration measurement only occurs when the vehicle is moving.

3.2. Effect of measurement time

Investigations of the effect of changing measurement times from 10 seconds through to full day exposures were carried out using an overlapping r.m.s. averaging moving window method (see Section 2). As expected, as the measurement duration increased, the vibration profile was smoothed. Results for one of the vehicles (a dumper truck) are shown in Figure 3. Similar trends in the smoothing of the data were obtained for all other vehicles.

For most vehicles, a spread in data points was retained for measurements of one minute duration. However, this was smoothed to being relatively constant throughout the day for 10 minute measurements. As measurement epochs increased, the smoothing improved, but variations in the data were still apparent. Similar results were obtained for vibration in the fore-aft and lateral directions, but are not presented here (see Mansfield and Atkinson, 2003).

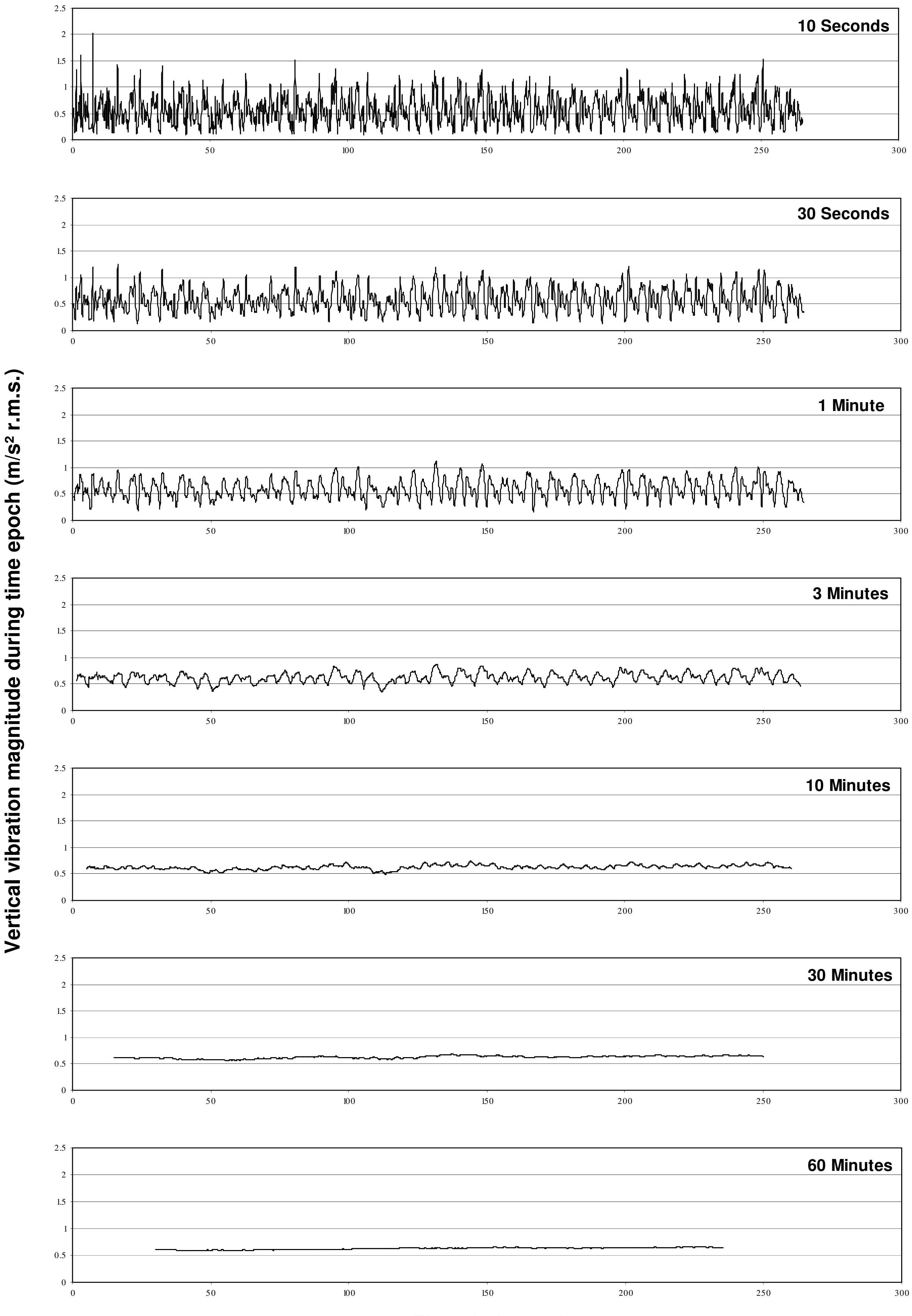

Figure 3. Vertical vibration measured on the seat of a dumper truck with measurement epochs ranging from 10 seconds to 60 minutes.

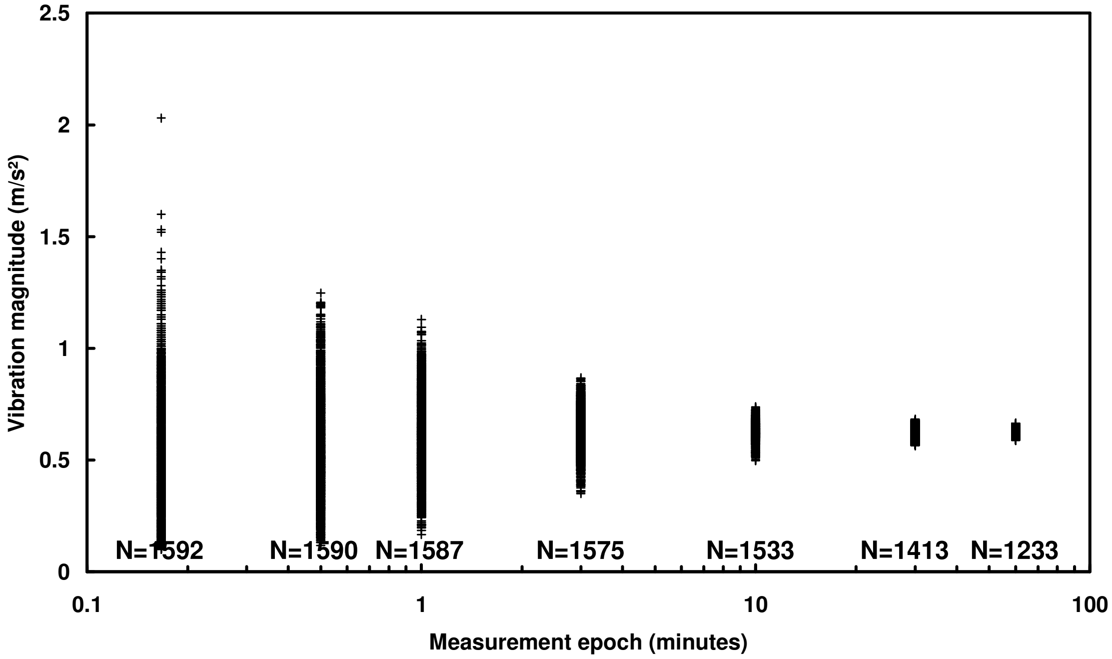

Figure 4. Individual measurements of vertical whole-body vibration measured on the seat of a dumper for measurement epochs ranging from 10 seconds to 1 hour. The number of measurements at each epoch range from 1233 to 1592.

4. Discussion

As the measurement epoch increases, the distribution of the possible measured values decreases. This is illustrated in Figure 4 which shows each individual possible measurement of whole body vibration during the day for each of the modelled time epochs for a dumper. Clearly, the results for measurements of 10 minutes or greater show less scatter than the results for measurements of one minute or less.

By measuring for the full working shift, these data have been able to generate the 'gold standard' vibration value that would be obtained for measurements lasting the full day. However, the question remains, how close is close enough for a shorter measurement? One criterion that could be used is to ensure that +/- 1 s.d. of the data is within the measurement error of a vibration meter. According to ISO8041 (1990), frequency weighting filters can have a tolerance of up to +/- 1 dB (equivalent to +/- 12%); for long term vibration measurement capability, the stability must be better than 3.5%; a sensitivity control must not introduce more than 3.5% error; in terms of linearity, the meter must have a tolerance of less than 8% error. For these tolerances, the total 'error' could be +/- 27%. Other tolerances are allowable in ISO8041 (e.g. cross-axis sensitivity, tolerance of calibration device, etc.).

Two criteria are considered here: how long must measurements last for +/- 1 s.d. of the data to be within 12.5% of the mean and how long must measurements last for +/- 1 s.d. of the data to be within 25% of the mean. These are close to the tolerances for the frequency weighting filter only and for most parts of the measurement device respectively. The coefficient of variation was calculated for each vehicle and each time epoch as:

$$\text{coefficient of variation} = \frac{\text{standard deviation}}{\text{mean}}$$

Coefficients of variation for the 20 vehicles are shown in Figure 5 and Table 2.

Vehicles in the same class showed generally similar trends (e.g. fire appliances, HGVs, vans and buses). For 60 minute epochs, vibration from all vehicles had a coefficient of variation of less than 12.5%. For 30 minute epochs, the only vehicle vibration that did not have a coefficient of variation of less than 12.5% was one of the loaders. All vehicles had a coefficient of variation of less than 25% for 10 minute epochs, but only 60% of them did for the 3 minute epoch. Three quarters of the vehicles did not meet either of the acceptance criteria for measurements lasting 1 minute. Road vehicles generally had lower coefficient of variations than the off-road vehicles (Figure 6), although the two sets of data converge as the epoch increases. These data indicate that, in general, a measurement epoch of at least 10 minutes is required to obtain reliable measurements if the measurement is started at any arbitrary time throughout the vibration exposure and that a measurement time of at least 30 minutes is preferable if +/- 1 s.d. of the data is to be within the tolerance of the frequency weighting.

Table 2. Coefficient of variation for measurements of vertical whole-body vibration in 20 vehicles for 7 different measurement epochs. Highlighted values correspond to coefficient of variations less than 25% and less than 12.5%.

vehicle	**Coefficient of variation**						
	10 sec	**30 sec**	**1 min**	**3 mins**	**10 mins**	**30 mins**	**60 mins**
bus	41%	30%	25%	**17%**	**10%**	**4%**	**2%**
bus	47%	33%	**24%**	**14%**	**8%**	**5%**	**4%**
bus	54%	38%	30%	**22%**	**16%**	**7%**	**4%**
car	29%	**24%**	**21%**	**15%**	**9%**	**6%**	**3%**
dumper truck	48%	39%	30%	**15%**	**7%**	**4%**	**3%**
dumper truck	60%	49%	41%	**23%**	**14%**	**9%**	**5%**
fire appliance	54%	46%	40%	31%	**19%**	**10%**	**1%**
fire appliance	49%	38%	32%	**24%**	**17%**	**5%**	**3%**
fire appliance	57%	48%	41%	33%	**22%**	**7%**	**1%**
fork lift truck	69%	52%	40%	27%	**14%**	**5%**	**2%**
HGV	46%	38%	32%	27%	**18%**	**9%**	**3%**
HGV	34%	26%	**21%**	**15%**	**10%**	**7%**	**5%**
HGV	34%	**24%**	**20%**	**13%**	**8%**	**4%**	**2%**
HGV	35%	27%	**23%**	**17%**	**12%**	**8%**	**7%**
land rover	44%	36%	32%	26%	**18%**	**8%**	**4%**
loader	55%	43%	37%	30%	**21%**	**15%**	**11%**
loader	72%	59%	52%	36%	**18%**	**6%**	**2%**
tractor	70%	56%	46%	27%	**14%**	**4%**	**2%**
van	54%	35%	25%	**14%**	**5%**	**2%**	**1%**
van	55%	40%	33%	**19%**	**10%**	**4%**	**1%**

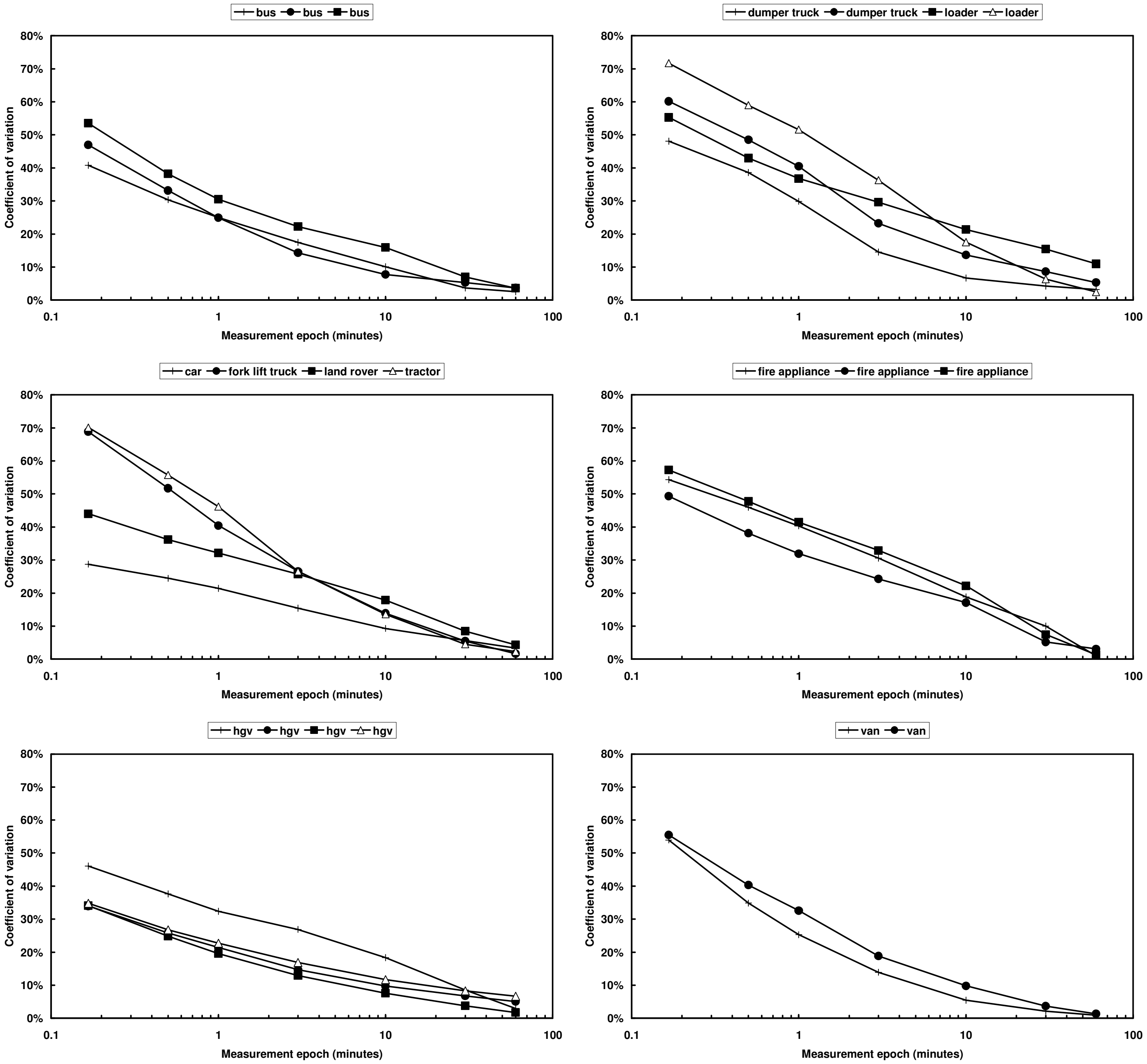

Figure 5. Coefficients of variation for measurements of vertical whole-body vibration in 20 vehicles for seven difference measurement epochs.

Even if measurements are made for the required times indicated here, they do no guarantee that the measurement will be close to the 'true' vibration exposure, as it is possible that the measure could be an outlier. About 32% of measurements will occur outside of +/- 1 s.d., assuming a normal distribution of vibration exposures.

A further important consideration is that these analyses are, by design, based on an entirely unintelligent algorithm that has not selected the most appropriate part(s) of the day to measure to simulate a worst case for an inexperienced investigator. It is likely that if the measurement period was selected carefully by an individual trained (and experienced) in vibration measurement, then the

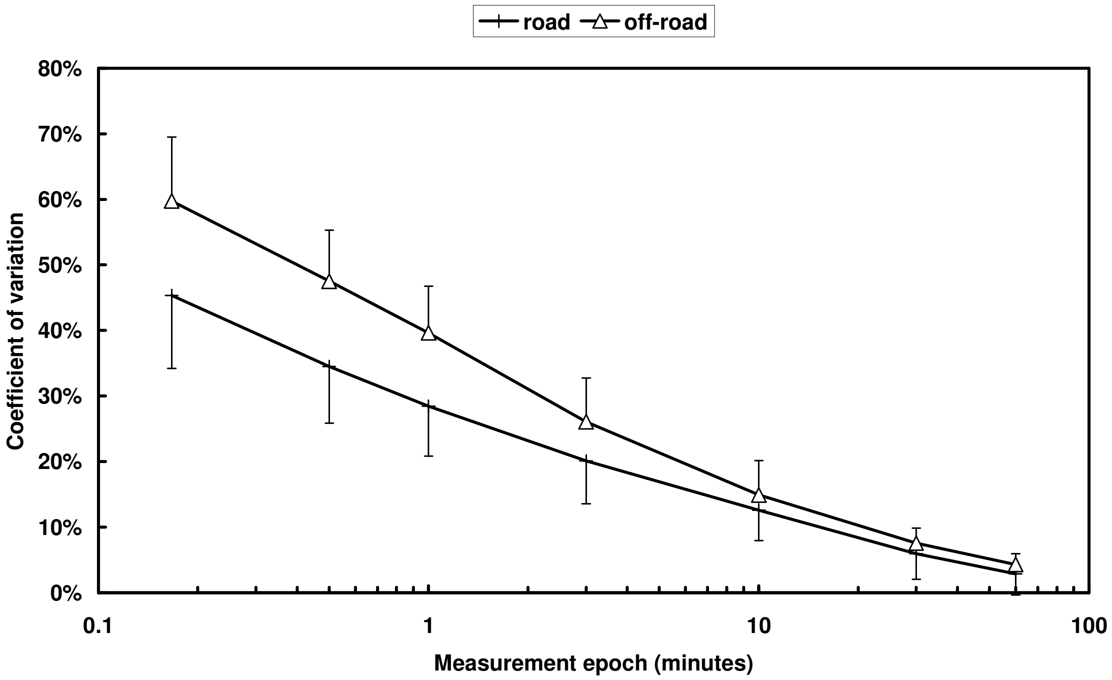

Figure 6. Mean coefficient of variation and standard deviations for road and off-road vehicles. Road vehicles are defined as buses, car, fire appliances, HGVs and vans. Off-road vehicles are defined as dumper trucks, fork lift truck, land rover, loaders and tractor.

variability would substantially decrease. Nevertheless, these data indicate that measurements as short as one minute should be avoided unless other constraints demand this epoch, as the variability is large.

Those tasked with measuring vibration on vehicles in the future might be tempted to fit data logging equipment to the machine that continuously measures for a period of time. These data show that such automatic logging of vibration exposures in vehicles might not be reliable unless long duration measurements are made. Also, in many vehicles it is inconvenient or impossible to continually monitor the vehicle's activity and therefore autonomous logging is essential. In these cases the investigator should be cautious and, if in doubt, measure for long periods.

5. Conclusions

Long term measurements of whole-body vibration in vehicles has shown that the stability of vibration measurements improves as vibration exposure time increases. The longer the duration, the better the probability that the measured value is close to the 'true' daily exposure. Measurements of whole-body vibration in vehicles should last at least 10 minutes, and ideally at least 30 minutes.

6. Acknowledgements

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7. References

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