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Shock and impact levels on North American locomotives

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Abstract

While whole body vibration (WBV) levels on North American locomotives are low, it has been suggested that isolated shocks and impacts in the overall vibration environment may pose greater health risks for crew members. In this paper, the shock and impacts measured on locomotives are evaluated through the vibration dose value (VDV) and spinal stress methods given in international standard ISO2631. More than 90 h of measurement data are used in this analysis.

This analysis found that shock and impact present a low probability of adverse health effects. For this data, the health guidance provided in ISO2631 for the VDV is more stringent than the health guidance for the spinal stress. The effects of occupant motion and other data artifacts are also discussed.

1. Introduction

The whole body vibration (WBV) levels evaluated with the basic root mean square (rms) acceleration method on North American locomotives are low relative to many other vehicle environments and comparable to the WBV levels in many highway vehicles [1–7]. The frequency-weighted rms acceleration levels do not reach the lower boundary of the health guidance caution zone given in international standard ISO 2631-1 [8]. However, it has been suggested that in general, isolated shocks and impacts in the overall vibration environment may pose greater health risks [9,10]. Johanning et al. [6] and Johanning et al. [7] claim that North American locomotive crew members are exposed to high shock and vibration levels, but base this claim on the erroneous assumption that high values of dimensionless ratios such as the crest factor indicate high shock levels.

This paper reports on shock and impact levels from more than 90 h of WBV and shock measurements on North American locomotives engaged in revenue service. The International Organization for Standardization (ISO) standards ISO2631-1 [8] and ISO2631-5 [11] provide three methods for evaluation of human exposure to vibrations that contain occasional shocks or impacts. ISO2631-1 specifies the running rms or maximum transient vibration value (MTVV), and the fourth power vibration dose value (VDV). Lewis and Griffin [12] report that VDV provides a more cautious assessment of the limiting daily exposure duration. ISO2631-5 [11]

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developed in response to concerns that high acceleration events may be particularly injurious [9,10], incorporates a fatigue approach to evaluate the stress in the lumbar spine of humans exposed to multiple shocks [9,13]. The VDV and spinal stress methods are reported and compared in this paper.

2. Locomotive and test descriptions

Locomotive and test descriptions for the 19 crew shifts reported in this paper are given in Table 1. The locomotives ranged from an EMD GP40-2 built in 1974 to a GE C44ACCTE built in 2004. The seats were not suspended and ranged from the low back, no arms, round seat "toadstool" types typical of the 1970s and shown in Fig. 1 to the current high back, lumbar support, adjustable arms units such as the USSC model 9010 shown in Fig. 2.

The measurements were taken in the period 2000–2005 at locations ranging from California to New York. Measurements were made over a full shift in order to evaluate the entire daily vibration exposure for the crew members. All were obtained continuously while the trains were moving with the exception cases E and L. In these cases, partial shift measurements for more than half the shift were extrapolated to the full shift with the assumption that the vibration characteristics for the full shift were the same as those during the measurement period. Measurement durations ranged from 188 to 497 min. A total of nearly 90 h of measurements are reported here.

All measurements were taken on trains operating in regular, revenue service. These included lower speed (mixed freight or manifest) trains, empty and loaded coal trains, and high-speed (priority or intermodal) trains. The trains were operated by the regular crew members called for duty in the normal manner. No instructions were given to the train crews for operation of the trains. All routes were mainline, continuously welded rail.

3. Data acquisition

The following instrumentation was utilized to acquire the WBV data analyzed in this study:

1. Triaxial Seatpad Accelerometer—Three Entran Devices EGA-F-10 peizoresistive accelerometers fixed within a 12 mm thick seat-pad assembly and attached to the seat cushion using duct tape. The seat pad conforms with ISO standard ISO10326-1 [14] and SAE standard SAE J1013 [15].

Table 1
Locomotive and route information

Case	Unit	Mfg date	Model	Test date	Duration (min)	Location
A	SP8240	1980	EMD SD40-2T	1/6/00	262	Sparks, NV-Roseville, CA
B	SP5350	1974	EMD SD40-2T	2/9/00	212	Dunsmuir-Klamath Falls
C	SP7600	1974	EMD GP40-2	8/21/01	284	Bakersfield-Lathrop (Stockton),
D	SP7600	1974	EMD GP40-2	8/21/01	301	Lathrop (Stockton)-Dunsmuir
E[a]	UP4008	2000	EMD SD70M	8/21/01	301	Lathrop (Stockton)-Dunsmuir
F	SP7600	1974	EMD GP40-2	8/22/01	255	Dunsmuir-Roseville
G	SP7613	1978	EMD GP40-2	8/23/01	187	Roseville-Fresno
H	CSX142	1996	GE AC4400	1/16/03	284	Selkirk(Albany)-Buffalo
I	UP6794	1996	GE 44AC	6/10/03	450	Fremont-North Platte
J	UP7126	1998	GE 44AC	6/11/03	497	North Platte-Fremont
K	UP9483	1993	GE C41-8W	6/12/03	395	Missouri Valley-North Platte
L[b]	UP9483	1993	GE C41-8W	6/13/03	208	North Platte-Fremont
M	UP8500	1998	EMD SD90AC	11/10/04	284	Cheyenne-North Platte
N	UP6263	1990	EMD SD60M	11/19/04	273	Green River-Cheyenne
O	UP5613	2004	GE C44ACCTE	1/18/05	188	North Platte-South Morrill
P	UP5613	2004	GE C44ACCTE	1/18/05	205	South Morrill-Bill, WY
Q	UP5613	2004	GE C44ACCTE	1/19/05	273	Bill, WY-South Morrill
R	UP5613	2004	GE C44ACCTE	1/20/05	229	South Morrill-North Platte
S	UP5613	2004	GE C44ACCTE	1/20/05	290	North Platte-Marysville, KS

[a]Data extrapolated to full shift.
[b]Partial shift.

Fig. 1. 1970 era locomotive seat.

2. Triaxial Chassis Accelerometer—Three Silicon Designs 2210-010 capacitive accelerometers (screened for a frequency response of ± 0.1 dB in the range of 0–100 Hz) fixed to a triaxial mounting block that utilized a magnetic base for attachment to the steel seat mounting structure.
3. Vehicle speed sensor—GMH Engineering DRS1000® Doppler microwave speed sensor. Vehicle speed is the most important variable affecting WBV levels. The speed sensor was generally attached to the side of the locomotive cab using a magnetic mount and pointed towards the ground at 45–60° from perpendicular.
4. Data Logger(s)—GMH Engineering DataBRICK II® data acquisition systems.
5. Sensor Signal Multiplexer (MUX)—A proprietary device designed to route the six accelerometer signals and one speed signal to the DataBRICK® actively acquiring data. Due to memory limitations, two DataBRICK® systems were used. While one system actively acquired a block of data the other system would upload a previously acquired block of data to a standard notebook computer.

The accelerometer channels were sampled at 400 samples/s and incorporated pre-sample, anti-aliasing filters set for a corner frequency of 100 Hz. The speed sensor digital signal required no anti-aliasing protection and was sampled at 10 samples/s. The data were acquired in 204.8 s blocks resulting in 81,920 samples for each accelerometer channel and 2048 samples for the speed channel.

The upload time for a single 204.8 s block of acquired data were approximately 180 s thus allowing a previously acquired block of data to be uploaded to the notebook computer, and the data logger memory cleared, while the second data logger was actively acquiring sensor data. This allowed for nearly continuous sampling of the sensor signals. Data were not acquired only during the few moments required to switch the

Fig. 2. Modern USSC locomotive seat.

MUX and trigger the waiting data logger. Occasionally, 2 or 3 min of data would be lost while previously acquired data blocks were inspected or other computer housekeeping tasks were performed.

The accelerometers and data loggers utilized in this study were calibrated at annual intervals. The calibrations were carried out according to usual and accepted metrology standards and documented with calibration certificates. The speed data for each test were corrected for the effect of the mounting angle using a calculated average speed between two or three mileposts on the route. The average speed was determined by hand timing the travel time between the selected mileposts using a stopwatch. The uncertainty associated with this speed calibration technique is conservatively estimated at $\pm 2\%$.

4. Data processing

Data processing was accomplished using the IGOR® scientific graphing and data analysis software environment. IGOR® is a product of WaveMetrics, Lake Oswego, Oregon. Each 204.8 s block of acquired data were stored and processed as a separate data file. The calculated results were determined for each data file individually and then globally for all data files acquired in a shift. Acceleration signals from the seat and floor transducers were processed following standards ISO2631-1 and ISO2631-5. These data were summarized in tabular form. The time signals were also processed to produce graphs that were used to evaluate anomalies in the data.

In the ISO2631-1 [8] processing, the continuous-time frequency-weighting functions were implemented as discrete-time functions in IGOR®. The rms values and crest factors called for in the basic method, as well as the fourth power VDV and the dimensionless VDV ratio were computed for each direction for each data block. Global values for the entire shift were also computed.

For the ISO2631-5 [11] processing, the horizontal spinal response model and the vertical spinal response model described in ISO2361-5 were also implemented in IGOR®. As described in ISO2631-5, the vertical spinal response model requires a sample rate of 160 samples/s for the input data to the model. Since the acceleration data used in this study were acquired at a sample rate of 400 samples/s, the vertical axis seatpad data were resampled to 160 samples/s for input to the vertical spinal response model.

The resampling process to convert the, as acquired, 400 samples/s data to 160 samples/s data involved the following three steps:

1. Upsample or interpolate the original 400 samples/s data to a new sample rate of 800 samples/s.
2. Low-pass filter the upsampled data using a corner frequency of 40 Hz. This was accomplished using an implementation of the 2-pole, 2-pass Butterworth filter specified in SAE J211.
3. Downsample or decimate the low-pass filtered 800 samples/s data to a new sample rate of 160 samples/s.

A thorough analysis and validation of the sample rate conversion process produced an observed uncertainty associated with the described resampling process of about 1%.

During the data processing and analysis stage, significant transients were observed in the seat-pad data that were not correlated with vehicle motion as determined by the chassis accelerometer. The seat-pad accelerometer accurately senses the WBV experienced by a seated occupant only when the occupant's weight is being supported by a load path that passes through the seat pad. Without the loading of a seated occupant, the seat-pad accelerometer responds to the motion of the unloaded seat cushion surface, which does not represent WBV. When a seat occupant sits, stands and or adjusts seating posture, the seat-pad accelerometer is generally exposed to relatively high acceleration transients that are not related to WBV. The fourth and sixth power calculations described in ISO2631 Parts 1 and 5 are particularly susceptible to corruption from non-WBV transients in the seat-pad data. The acceleration data acquired from the chassis accelerometer allows transients observed in the seat-pad data to be evaluated and characterized as either true WBV (correlated with the vehicle motion) or artifacts of voluntary occupant motion (uncorrelated with the vehicle motion). Fig. 3 shows an example of a transient in the seat-pad data that was obviously not correlated with vehicle motion. In this case, the seat occupant repeatedly lifted from and returned to the seat over an approximate 10 s period. Fig. 4 shows an example of a transient in the seat-pad data that was clearly correlated with the vehicle motion.

Figs. 3 and 4 also illustrate the significantly different system natural frequencies associated with a loaded, versus an unloaded seat pad–cushion system. The uncorrelated transients in Fig. 3, clearly exhibit the characteristic higher natural frequency that would be associated with the lower mass of an unloaded seat-pad—seat-cushion system. While not as reliable as the use of a chassis accelerometer, the frequency content of transients in seat-pad data can also be used to assist in determining whether or not a given transient is in fact WBV or an artifact of voluntary seat occupant motion.

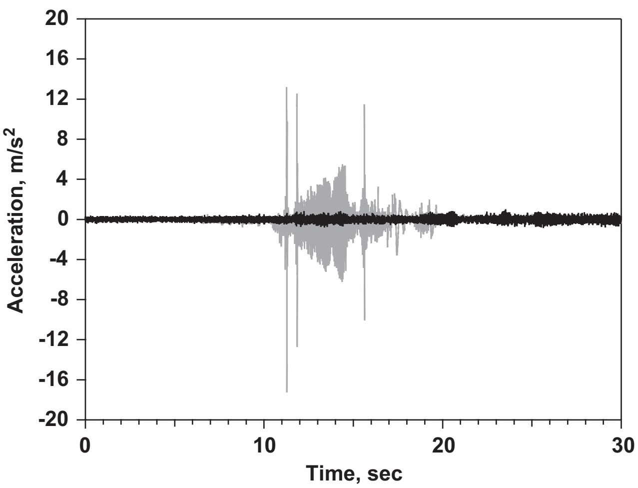

Fig. 3. Uncorrelated seat-pad acceleration. ▬ Floor vertical, ▬ seat vertical.

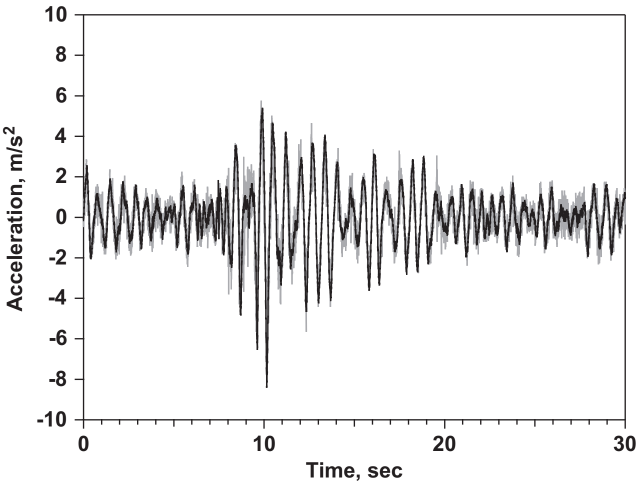

Fig. 4. Correlated seat-pad acceleration. ▬ Floor vertical, ▬ seat vertical.

For the purposes of this study, each 204.8 s block of acquired data were screened for seat-pad transients that were not correlated with the vehicle motion. When uncorrelated transients of significant magnitude were found, the entire 204.8 s data set was excluded from the WBV analysis. This methodology complies with the provisions described in the European Standard EN14253 [16].

5. Results

5.1. Basic method

The basic method given in standard ISO 2631-1 for evaluating the human response to vibration exposure, as discussed above, involves computing the rms value of the acceleration signal weighted for the variation in human sensitivity with frequency. The average speed for the shift as well as the weighted rms values in each of three directions for the full shifts reported here are given in Table 2. These values are graphically shown in Fig. 5.

In most cases, the vertical weighted rms acceleration levels were considerably higher than the levels in the longitudinal and lateral directions. In cases A and B, measurements taken on mountainous routes with low speeds and numerous curves, the lateral and vertical levels were comparable although these levels were quite low.

Standard ISO 2631-1 provides guidance to interpret the possible health effects of vibration exposure. The standard states that the assessment of vibration should be made independently along each axis. It identifies a health guidance caution zone above which ‘‘health risks are likely’’ and below which ‘‘health effects have not been clearly documented and/or objectively observed.’’ These boundaries depend on the duration of exposure; lower exposure is allowed for longer durations. For example, at 8 h of exposure, the lower boundary is approximately $0.50\,m/s^2$, and for the daily exposures reported here, all for periods shorter than 8 h, the lower boundary is even higher. In all the cases given in Table 2, the weighted rms acceleration levels are below the lower boundary of the health guidance caution zone.

To evaluate the possible importance of isolated shocks or impacts during exposure to vibration, ISO 2631 specifies calculation of the crest factor defined as the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its rms value. The standard notes that the ‘‘crest factor does not necessarily indicate the severity of vibration.’’ If the crest factor exceeds 9, the standard recommends computation of the VDV or mean transient vibration value (MTVV) as a further basis for judgment of the influence on human beings.

The crest factors in each direction computed for the full shift are given in Table 2. With three exceptions, these values exceed 9. This is not surprising given the long data acquisition periods. One brief period of high

Table 2
Locomotive WBV measurements

Case	Speed (kph)	W_{rms}			Crest factor			VDV			$VDV/a_wT^{.25}$			S_{ed} (MPa)
		$a_{x\,rrms}$ m/s^2	$a_{y\,rms}$ (m/s^2)	$a_{z\,rrms}$ (m/s^2)	x	y	z	VDV_x (m/s$^{1.75}$)	VDV_y (m/s$^{1.75}$)	VDV_z (m/s$^{1.75}$)	x	y	z	
A	33.8	0.0549	0.1246	0.1364	26.7	35.1	46.0	1.90	4.74	3.97	2.54	2.68	2.58	0.128
B	39.9	0.0722	0.1207	0.1668	12.0	16.3	11.8	1.31	2.50	2.67	1.65	1.65	1.51	0.162
C	42.8	0.1197	0.2001	0.4581	11.9	10.8	14.8	2.19	3.65	9.21	1.60	1.60	1.76	0.434
D	51.2	0.1216	0.2384	0.4473	12.2	7.5	14.3	2.33	4.13	9.17	1.65	1.49	1.77	0.383
E[a]	51.7	0.2050	0.1991	0.3492	12.0	12.0	8.7	4.15	3.99	6.49	1.75	1.73	1.60	0.250
F	56.3	0.2060	0.2345	0.4493	9.5	8.7	14.0	3.47	4.13	9.17	1.51	1.58	1.84	0.337
G	59.9	0.1216	0.1884	0.3041	19.9	16.2	29.0	2.43	3.16	6.12	1.94	1.63	1.96	0.302
H	60.0	0.0863	0.1933	0.2747	19.2	13.5	28.6	1.66	4.01	5.13	1.68	1.82	1.64	0.260
I	62.0	0.1383	0.1373	0.3698	12.9	10.7	12.3	2.57	2.54	6.17	1.45	1.44	1.30	0.213
J	62.9	0.1099	0.1442	0.3090	18.0	31.4	12.1	2.31	3.77	6.02	1.60	1.99	1.48	0.226
K	63.5	0.1687	0.2090	0.5219	12.6	15.4	9.4	3.38	3.77	9.33	1.61	1.45	1.44	0.317
L[b]	64.2	0.1481	0.2011	0.4885	13.2	9.7	11.8	2.68	3.17	7.85	1.71	1.49	1.52	0.302
M	64.2	0.1148	0.1275	0.3895	11.0	14.5	9.6	2.20	2.52	6.81	1.68	1.73	1.53	0.200
N	66.1	0.1285	0.2914	0.3669	11.8	13.3	14.5	2.50	6.40	7.10	1.72	1.94	1.71	0.349
O	66.8	0.0716	0.1138	0.1854	10.1	12.1	17.2	1.25	1.88	3.17	1.69	1.60	1.66	0.130
P	67.4	0.0608	0.1226	0.1570	26.2	12.8	11.8	1.23	2.13	2.68	1.92	1.65	1.62	0.123
Q	75.8	0.0775	0.1109	0.1717	13.2	11.9	10.6	1.39	2.08	2.99	1.59	1.66	1.54	0.126
R	80.9	0.0814	0.1050	0.1785	25.7	14.2	17.0	1.63	1.98	3.58	1.85	1.74	1.85	0.149
S	87.8	0.0804	0.1187	0.1874	15.4	13.4	14.4	1.73	2.35	3.93	1.87	1.72	1.83	0.172

[a]Data extrapolated to full shift.
[b]Partial shift.

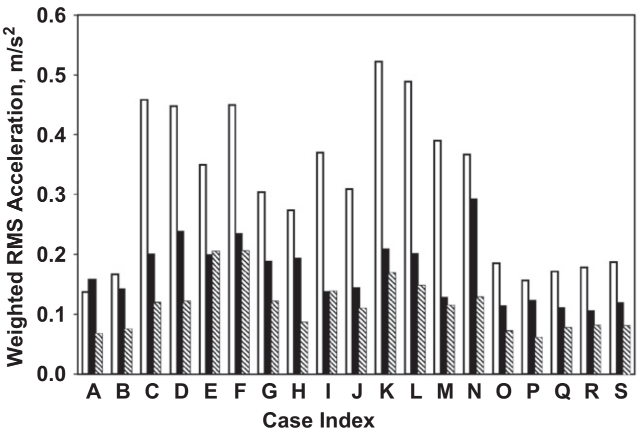

Fig. 5. Weighted rms acceleration. □ Vertical, ■ lateral, ▧ longitudinal.

vibration levels during a long but low level of vibration exposure will produce a high crest factor. Note that the highest crest factor, 46.0 in the vertical direction in Case A, occurred on a low speed run with low overall weighted rms acceleration levels.

5.2. VDV

The VDVs for each shift are also given in Table 2. The ISO2631-1 standard provides for computing the VDV or the maximum transient vibration value (MTVV) in cases where the crest factor exceeds 9. The MTVV was not reported for these measurements because it only describes the highest 1 s acceleration period which is

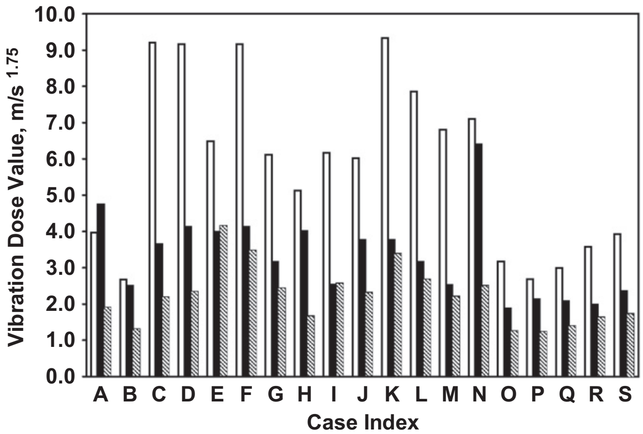

Fig. 6. Vibration dose values (VDVs). □ Vertical, ■ lateral, ▨ longitudinal.

not meaningful for measurement periods as long as 27,000 s. Also, neither ISO2631-1 nor any other source provides any guidance to use with the MTVV in evaluating health effects of vibration and shock exposure.

The VDV is based on a fourth power averaging of the weighted acceleration exposure and as such emphasizes the larger acceleration values more heavily than the second power average of the rms computation. Fig. 6 illustrates the VDV results for the 19 cases reported here. Comparison with Fig. 5 shows that in all but one case a direct and nearly linear relationship exists between the weighted rms acceleration values and the VDVs. In other words, the higher the weighted rms the higher the VDV, and the rank order of vibration levels was the same (with the one exception) for either method.

The ISO2631-1 standard gives indirect guidance for health exposure evaluation using the VDV. The standard states that the estimated VDVs corresponding to the lower and upper bounds of the zone for the weighted rms acceleration values are 8.5 and 17, respectively. The estimated VDV values are computed using the rms acceleration and the duration of the measurement and in the measurements reported here are in all but one case lower than the actual VDVs. Nonetheless, the standard is often interpreted to state that the lower boundary of the health guidance zone for VDVs is 8.5 and the upper 17. With this interpretation, four of the cases reported here exceeded the lower boundary for vibration in the vertical direction. In the lateral and longitudinal directions, ISO2631-1 states that the multiplying factor, 1.4, should be applied for health evaluation of seated persons. In five of the cases in Table 2, the lateral VDV with the 1.4 factor exceeds the vertical VDV and in one case, case N, the lateral VDV multiplied by 1.4 is 8.96, slightly in excess of the lower boundary of the health guidance caution zone.

The ISO2631-1 standard also states that experience suggests that the VDV method for evaluating the effects of vibration on human beings will be important when the ratio, $\mathrm{VDV}/(a_w T^{1/4})$, exceeds 1.75. Note that this ratio is suggested for guidance as to when the VDV method may be important, but does not provide health guidance. Like the crest factor, this ratio does not necessarily indicate the severity of the vibration. Johanning et al. [6,7] misinterpret this section of the standard and suggest that high VDV ratios indicate unhealthy levels of vibration.

The VDV ratios for the vertical direction in Table 2 exceed 1.75 in seven cases. The corresponding VDVs for these cases range from 3.58 to 9.21, clearly illustrating that there is no correlation between the VDV ratio and the actual VDV.

5.3. ISO 2631 Part 5 method

In 2004, the ISO adopted part 5 of the ISO 2631 standard [11]. As explained earlier, this part defined a method of quantifying WBV containing multiple shocks in relation to human health. The daily equivalent static compression dose value, S_{ed}, computed following this standard for the 19 crew shifts reported here are given in Table 2. These values range from 0.123 to 0.434 MPa. The health guidance provided in Ref. [11] states

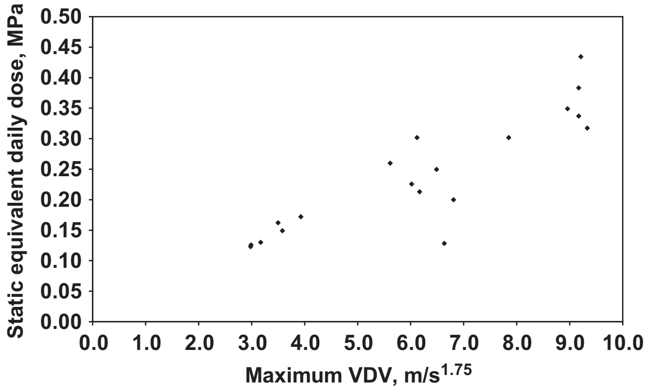

Fig. 7. Static compression dose versus VDV.

that if the daily equivalent static compression dose value is below 0.5 MPa, there is a low probability of an adverse health effect for a worker exposed to this vibration 240 days a year for a working life of 45 years (aged 20–65 years). Thus, an ISO 2631-5 evaluation suggests that the vibration and shock levels measured for these 19 shifts do not pose a health risk to the locomotive crew members.

In Fig. 7, the daily equivalent static compression dose is plotted against the maximum VDV, where the maximum VDV is defined to be the larger of the vertical VDV or the lateral VDV with the 1.4 multiplying factor. A roughly linear correlation of the S_{ed} with the maximum VDV is evident in the graph. Note that although the highest VDV values exceed the lower health guidance boundary of 8.5, all the S_{ed} values are well below the boundary for low probability of an adverse health effect with daily exposure over a lifetime of work.

These results, where the VDV evaluation is more stringent than the daily equivalent static compression dose evaluation, are quite different than those reported for military vehicles [17]. For military vehicles, Alem et al. found the opposite, that the S_{ed} evaluation was far more stringent than the VDV evaluation. The explanation for this most likely lies in differences in the characteristics of the locomotive and military impact environments. The cross-country rough terrain and relatively lower speeds experienced by the military vehicles apparently produces fewer but higher magnitude impacts that are weighed more heavily in the sixth power approach used in ISO2631-5.

5.4. *Effects of occupant motion*

As discussed above and illustrated in Figs. 3 and 4, data anomalies due to occupant motion or the occupant leaving the seat can have a very large influence on the VDV and S_{ed} levels. For a short period during one file (204.8 s period) in the Case K, the seat occupant adjusted himself in the seat and large peaks occurred in all directions. As a result, the lateral VDV for this file was 4.68 m/s$^{1.75}$, a level much larger than any other period during that run. If this file and two other files with anomalies had been included in the overall lateral VDV, the VDV would have increased from 3.77 to 5.14 m/s$^{1.75}$.

The effects on the daily equivalent compression dose, S_{ed} are even greater. The lateral spinal dose for the same file was 15.94 MPa, much larger than the highest, 5.92 MPa stress level for all other files in that run. If this file had been included in the daily spinal stress value, it would have risen from 0.302 to 0.561 MPa, a very dramatic effect for a disturbance that lasted only a few seconds and had a peak value of 1.39 g.

6. Conclusions

The following conclusions may be drawn from the results presented here:

1. The crest factor, VDV and MTVV dimensionless ratios given in ISO2631-1 do not indicate whether or not isolated shocks are large enough to pose health risks. When the underlying vibration levels are low these

ratios may exceed the guidelines for further evaluation given in ISO2631-1 even though the shock levels are benign. This is the case for the locomotive vibration environments we measured. Given that the VDV and MTVV are easily calculated, and must be calculated to get the VDV and MTVV ratios, the ratios do not provide any useful information. It would make sense to remove these ratios from the ISO2631-1 standard.
2. For the locomotive measurements presented here, an approximately linear correlation exists between the daily spinal stress, S_{ed}, and the maximum VDV. Although the highest VDV values exceed the lower health guidance boundary of 8.5, all the S_{ed} values are well below the boundary for low probability of an adverse health effect with daily exposure over a lifetime of work. Thus, for this data the health guidance concerning the VDV in ISO2631-1 is more stringent than the health guidance concerning the S_{ed} in ISO2631-5. In future versions of these standards, this inconsistency should be addressed.
3. Occupant motions or other artifacts may have a large effect on the VDV and spinal stress values. In order to obtain values that properly reflect impact exposure it is essential that these artifacts are identified and removed during the data analysis procedure.
4. Evaluation of the data collected in the studies reported here according to the health guidance in ISO 2631 indicates that the shock and impact exposure for locomotive crew members presents a low probability for an adverse health outcome.

Acknowledgments

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