The XXXIIIrd Annual International Occupational Ergonomics and Safety Conference
Virtual Conference
September 16-17, 2021

Whole-Body Vibration Exposure For North American Locomotive Train Crews: An Update

Steve D. Fleming[1], George B. Page[1], Greg G. Weames[2]

[1]Page Engineering, Inc., Jackson, Michigan, United States of America

[2]Page Engineering, Inc., Georgetown, Ontario, Canada

Corresponding author's Email: steve@pageengineering.net

Abstract: Health and safety professionals have been attentive to whole-body vibration (WBV) exposure assessments for North American train crews since the 1970s. A compilation of 220.4 hours of WBV exposure data is presented based on WBV assessments by Page Engineering, Inc. WBV exposure data consisting of 32 through-freight train runs, 2 yard jobs, and 1 local train run, were collected between 2009 and 2020 at locations across the United States. WBV exposure assessments were conducted according to ISO 2631-1 (1997) and ISO 2631-5 (2004). Basic acceleration (RMS), vibration dose value (VDV), and the daily equivalent static compression dose (S_{ed}) were evaluated. All data were collected according to a developed "gold standard". The "gold standard" required seated WBV exposure to be measured over the entire duration of exposure, for regularly assigned train runs/jobs, and for all artifacts to be removed from the data prior to processing. The average results were RMS_z=0.22 m/s^2, VDV_z=4.75 m/s$^{1.75}$ and S_{ed}=0.24 MPa. There was no result for any train run that exceeded the lower boundaries for any of RMS, VDV and S_{ed}. This data compilation indicates that North American train crews are not at increased relative risk for the development of musculoskeletal disorders of the lumbar spine.

Keywords: Whole-Body Vibration, Locomotive, Health Guidance

1. Introduction

WBV exposure for members of train crews operating on freight locomotives has been assessed since the mid-1970s (FRA, 1972). The earlier assessment efforts were in conformance with ISO 2631 (1974). In 1997, the ISO WBV committee revised the WBV standard and introduced the application of a "Health Guidance Caution Zone" (HGCZ). At this time, ISO 2631 (1997) also introduced additional analysis and health guidance for WBV exposures that likely contain discrete shocks and jolts that have the potential to have more dramatic influence on spinal health. This additional analysis was termed vibration dose value (VDV), and ISO 2631 (1997) provided a HGCZ for this metric. In 2004 the ISO committee introduced evaluation of WBV exposure assessment that determined long-term exposure, over several years, and termed this evaluation as the static compression dose (S_{ed}). Subsequent to 2004 there have been efforts to measure and report on the more recent ISO standards and HGCZ regarding WBV exposure for employees working on freight locomotives (Larson et al., 2006; Johanning et al., 2006; Cooperrider & Gordon, 2008; Page et al., 2010a; Page et al., 2010b; Page et al., 2010c; Weames et al., 2014; Page et al., 2015).

The concept of a "gold standard" has been proposed for WBV exposure assessment (Page et al., 2016; Weames et al., 2016; Fleming et al., 2020; Weames et al., 2021). The proposed "gold standard" requires that the WBV exposure measurement be done during actual working conditions, be done over the entire duration of seated exposure, and that all occurrences of artifact be removed. Artifacts are those moments of the accelerometer excitation that are irrelevant with the source vehicular vibration. A common example of an artifact relevant to WBV exposure is when the subject that is under investigation gets out of and into their measured seating system.

The purpose of this paper is to contribute to the body of research of WBV exposure of seated occupants on North American freight locomotives in accordance with a proposed "gold standard" for WBV assessment.

2. Methods

220.4 hours of WBV data were collected during 32 through-freight train runs, 2 yard jobs, and 1 local train run from 2009 to 2020. The locomotives were manufactured by GE and EMD between 1964 and 2014. The locomotive top speeds ranged from 10 to 70 MPH. Table 1 shows additional information on each of the 35 train runs/jobs regarding the date of measurement, the origin and destination, the duration of exposure, type of train service, and the details of the locomotive. The

ISBN: 97819384965-9-2

https://doi.org/10.47461/isoes.2021_055

instrumentation and setup for data collection (see Figure 1) consisted of a 10G tri-axial accelerometer mounted in a flat disk and affixed to the seat pan of the locomotive seating system and a second 10G tri-axial accelerometer mounted on the framework under the seat pan. Both accelerometers were connected to a Biometrics DataLog data acquisition device set to record each channel at 500 Hz. A GPS unit was used to track the speed of the locomotive at 1-second intervals. A continuous video record of the seat occupant was collected and synchronized to the accelerometer data. An LED indent switch was connected to the DataLog device to synchronize the video with the WBV data record. The indent switch was also used to mark occurrences of interest, such as identified track conditions, during data collection.

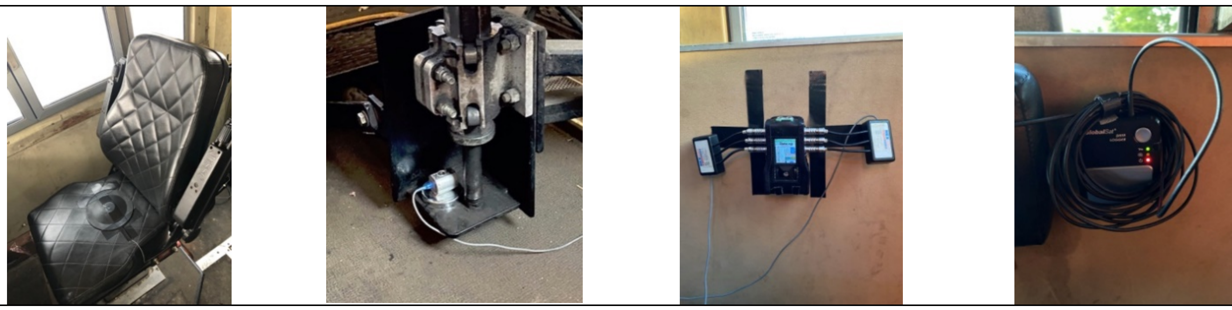

Figure 1: Instrumentation (left to right): Seat pan accelerometer, frame accelerometer, WBV data logger, and GPS.

For the video record, up to four synchronized camera views were used (see Figure 2). The top two camera views are useful when confirming occupant-induced artifacts. The windshield view shows the track conditions, train movement, and milepost information. The positive train control (PTC) screen provides detailed information about the train's current state of operation, such as the speed, grade, milepost, and the locations of speed restrictions. The video record was used to support comprehensive identification and removal of artifact and to provide records on progress and actions of the work performed.

WBV assessments were conducted and analyzed following procedures specified by ISO and ANSI standards (ANSI, 2002; ISO 1997/2010; ISO 2004). Basic vibration (RMS), VDV, and S_{ed} were calculated using the Vibration Analysis Tool Set (VATS) software, developed by NexGen Ergonomics, Inc. The results were applied to the HGCZ of ISO 2631-1 and the boundaries defined by ISO 2631-5.

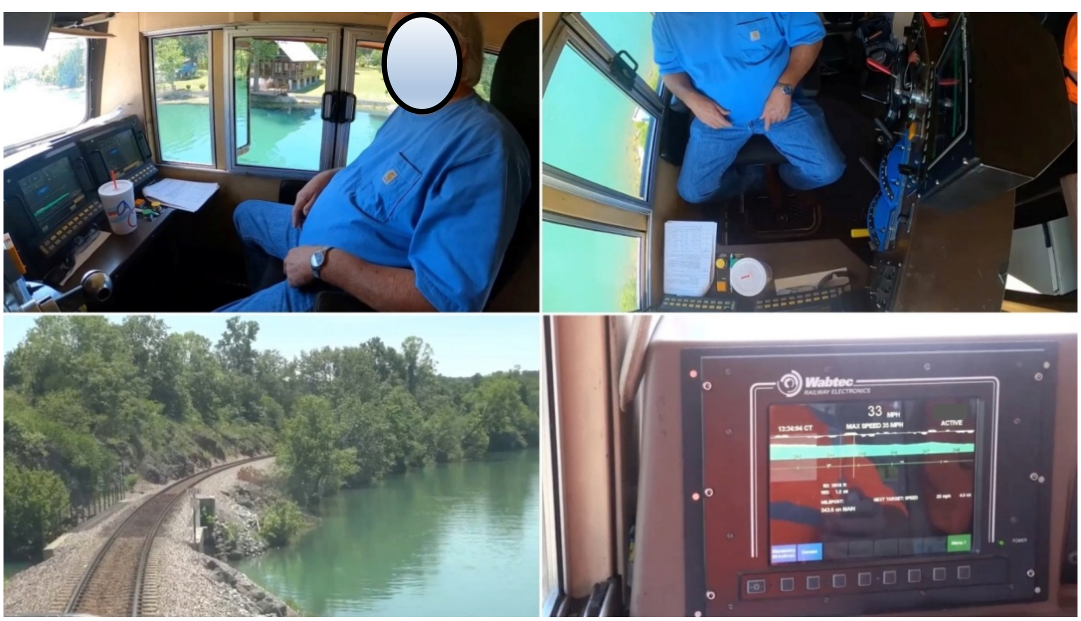

Figure 2: Four synchronized camera angles (clockwise from upper left):
Sagittal view, overhead view, locomotive computer screen, windshield view.

Table 1. Train Run Data.

	Date	Origin	Destination	Exposure Time (Hr)	Max Speed (MPH)	Service Type	Identifier	Model	Year Built	Crew Position	Seat
1	11/30/09	Silverbow, MT	Dillon, ID	3.96	40.11	TF	UP 3412	SD40-2R	1980	E	USSC
2	12/01/09	Dillon, ID	Idaho Falls, ID	4.86	41.66	TF	UP 3412	SD40-2R	1980	E	USSC
3	12/01/09	Idaho Falls, ID	Dubois, ID	1.66	40.92	TF	UP 3465	SD40-2R	1978	E	USSC
4	12/15/09	Del Rio, TX	Alpine, TX	7.06	48.10	TF	UP 7909	C45AC	2008	E	USSC
5	07/21/10	Bill, WY	Gillette, WY	3.21	47.94	TF	UP 6726	C44AC	1994	E	USSC
6	07/21/10	Gillette, WY	Bill, WY	3.80	42.28	TF	UP 6787	C44AC	1996	E	USSC
7	02/15/11	Blaine, WA	Everett, WA	5.65	52.60	TF	BNSF 5122	C44-9W	2004	E	USSC
8	03/30/11	Mineola, TX	North Little Rock, AR	8.56	54.52	TF	UP 8455	SD70ACE	2006	C	Seats Inc.
9	05/24/11	Chewelah, WA	Spokane, WA	6.83	27.80	L	BNSF 3120	GP50	1985	E	Seats Inc.
10	05/25/11	Spokane, WA	Wenatchee, WA	6.06	61.20	TF	BNSF 5424	C44-9W	2000	E	USSC
11	05/26/11	Spokane, WA	Pasco, WA	5.54	60.40	TF	BNSF 4529	C44-9W	1999	E	USSC
12	03/07/13	Kansas City, KS	Jefferson City, MO	9.09	49.06	TF	UP 6009	C44ACCTE	2003	E	USSC
13	03/08/13	Jefferson City, MO	Kansas City, MO	6.61	55.70	TF	UP 5852	C44ACCTE	2002	E	USSC
14	03/15/13	Missouri Valley, IA	Clinton, IA	7.50	69.86	TF	UP 7774	C45ACCTE	2007	C	USSC
15	06/25/13	Marysville, KS	Kansas City, MO	7.16	50.74	TF	UP 6044	C44ACCTE	2004	E	USSC
16	04/08/14	Boone, IA	Fremont, NE	5.82	63.22	TF	UP 7486	C45ACCTE	2011	E	Seats Inc.
17	11/20/14	Sioux City, IA	Willmar, MN	6.13	53.72	TF	BNSF 8245	ES44C4	n/a	E	Baultar
18	03/31/15	Marion, SD	Sioux Falls, SD	5.26	28.26	TF	BNSF 6298	ES44AC	2008	E	Baultar
19	04/01/15	St. Louis, MO	Quincy, MO	6.07	45.95	TF	BNSF 4962	C44-9W	1998	E	USSC
20	04/12/15	Willmar, MN	Sioux City, IA	7.41	51.11	TF	BNSF 4014	C44-9W	2003	E	Seats Inc.
21	04/13/15	Sioux City, IA	Willmar, MN	8.43	51.42	TF	BNSF 6036	ES44AC	2006	E	Baultar
22	04/28/15	Sioux City, IA	Mitchell, SD	6.07	40.18	TF	BNSF 2896	GP39-2	1964	E	Seats Inc.
23	12/15/15	Van Buren, AR	Coffeyville, KS	8.55	49.25	TF	UP 6869	C44AC	1995	E	USSC
24	12/16/15	Coffeyville, KS	Fort Gibson, OK	5.33	50.11	TF	UP 6475	C44AC	2000	E	USSC
25	01/07/16	Parsons, KS	Van Buren, AR	7.97	50.36	TF	UP 8716	SD70ACE	2012	E	Seats Inc.
26	05/24/16	Missouri Valley, IA	North Platte, NE	7.60	51.92	TF	UP 7935	C45ACCTE	2012	E	Seats Inc.
27	05/25/16	North Platte, NE	Council Bluffs, IA	8.15	52.54	TF	UP 8448	SD70AH	2014	E	Seats Inc.
28	08/02/16	Northtown, MN	Dilworth, MN	7.86	55.14	TF	BNSF 6844	ES44C4	2011	E	Baultar
29	05/15/18	Winslow, AZ	Belen, NM	7.48	70.73	TF	BNSF 6390	ES44AC	2009	E	Baultar
30	04/30/19	Fresno, CA	Fresno, CA	5.65	42.10	Y	UP 1131	GP60	1988	E	USSC
31	12/03/19	North Platte, NE	Cheyenne, WY	8.47	52.04	TF	UP 7865	C45ACCTE	2008	E	USSC
32	12/17/19	Kansas City, MO	Kansas City, MO	5.67	10.31	Y	KCS 3903	SD70MACE	1999	E	Seats Inc.
33	02/19/20	Bill, WY	Gillette, WY	2.33	69.24	TF	UP 6695	C44AC	1997	C	USSC
34	08/17/20	Thayer, MO	Memphis, TN	7.12	54.71	TF	BNSF 5973	ES44AC	2006	E	Baultar
35	10/13/20	Lincoln, NE	Ravenna, NE	5.47	48.56	TF	BNSF 6256	ES44AC	2008	E	Seats Inc.

TF=through-freight, L=local, Y=yard, E=engineer, C=conductor

3. Results

The ISO 2631-1 HGCZ boundaries for RMS are exposure time dependent. The average WBV exposure time for the 35 train runs/jobs was 6.3 hours (see Table 2). At 6.3 hours of exposure, the lower boundary of the HGCZ is 0.488 m/s^2 and the upper boundary of the HGCZ is 0.976 m/s^2. The VDV HGCZ is defined by a lower boundary of 8.5 m/s$^{1.75}$ and an upper boundary of 17.0 m/s$^{1.75}$. The dominant axis based on the average of the 35 train runs/jobs for RMS and VDV was the z-axis. ISO 2631-1 Annex B RMS health guidance was based mostly on human response to z-axis vibration experienced by seated persons, while the x-axis and y-axis research experience was limited. The average z-axis RMS (RMS_z) value of 0.22 m/s^2 and the average z-axis VDV (VDV_z) value of 4.75 m/s$^{1.75}$ were both below their respective lower boundaries of the HGCZ. All train runs/jobs in Table 2 individually resulted in RMS and VDV values, for any single axis, below their respective lower boundaries of the ISO 2631-1 HGCZ. Train runs/jobs with comparable dominant RMS axes were investigated for their vector sum total vibration, as proposed in ISO 2631-1, and were also below the single axis based HGCZ lower boundary.

The ISO 2631-5 HGCZ daily equivalent static compression dose (S_{ed}) lower boundary is 0.5 MPa and the upper boundary is 0.8 MPa. All three accelerometer axes are considered in the S_{ed} calculation, which is based on the observed daily exposure extrapolated over 240 days per year, for 45 years, beginning at age 20. The average S_{ed} value for the 35 train runs/jobs was 0.24 MPa, which is below the lower boundary. Table 2 shows that the S_{ed} value was below the lower boundary for each of the 35 individual train runs/jobs.

Table 2. Locomotive WBV Assessment Results.

	RMS_x (m/s^2)	RMS_y (m/s^2)	RMS_z (m/s^2)	VDV_x ($m/s^{1.75}$)	VDV_y ($m/s^{1.75}$)	VDV_z ($m/s^{1.75}$)	S_{ed} (MPa)
1	0.11	0.30	0.19	2.39	5.55	5.03	0.29
2	0.19	0.26	0.35	4.07	4.47	8.28	0.43
3	0.28	0.36	0.47	4.22	4.86	7.64	0.41
4	0.12	0.16	0.27	2.28	2.92	4.82	0.19
5	0.08	0.14	0.17	1.70	2.49	2.88	0.16
6	0.10	0.13	0.22	3.05	2.50	3.41	0.16
7	0.15	0.16	0.16	2.18	2.38	3.36	0.17
8	0.11	0.19	0.25	3.11	4.22	4.92	0.20
9	0.14	0.21	0.21	3.58	4.62	4.28	0.21
10	0.11	0.17	0.22	2.65	3.37	5.03	0.21
11	0.11	0.15	0.21	2.34	3.18	4.65	0.22
12	0.10	0.12	0.19	2.43	2.92	5.17	0.29
13	0.08	0.13	0.21	1.78	2.95	4.62	0.22
14	0.17	0.21	0.34	3.74	4.48	7.50	0.31
15	0.14	0.17	0.23	3.18	3.78	6.04	0.36
16	0.14	0.19	0.28	3.03	4.10	5.99	0.27
17	0.15	0.21	0.36	2.97	4.10	7.78	0.42
18	0.07	0.09	0.12	2.56	1.86	2.37	0.13
19	0.15	0.20	0.23	3.19	3.81	6.06	0.29
20	0.08	0.11	0.11	2.58	2.23	2.17	0.12
21	0.07	0.10	0.10	1.73	2.19	2.26	0.12
22	0.12	0.14	0.14	4.14	2.70	2.62	0.17
23	0.11	0.15	0.18	2.68	3.33	4.11	0.18
24	0.11	0.14	0.28	2.90	2.99	4.73	0.20
25	0.13	0.16	0.21	2.90	3.40	6.04	0.35
26	0.12	0.15	0.22	3.04	3.22	4.69	0.21
27	0.12	0.15	0.21	2.66	3.50	4.77	0.24
28	0.18	0.17	0.34	4.30	3.70	7.12	0.33
29	0.15	0.24	0.29	3.11	5.20	6.00	0.26
30	0.11	0.13	0.14	3.97	2.81	3.43	0.19
31	0.12	0.13	0.19	2.56	2.84	3.83	0.18
32	0.07	0.06	0.12	2.11	1.41	2.71	0.12
33	0.14	0.19	0.19	2.28	2.94	3.15	0.17
34	0.11	0.21	0.19	2.72	4.75	4.84	0.28
35	0.09	0.12	0.18	2.51	2.80	3.88	0.18
Average	0.12	0.17	0.22	2.88	3.39	4.75	0.24

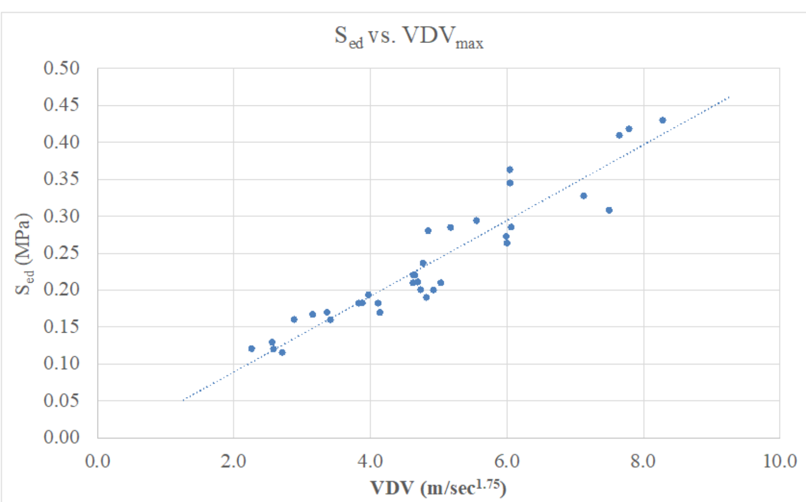

Figure 3. Plot of S_{ed} vs. Dominant VDV (VDV_{max}) for Each Train Run/Job.

Artifact removal was very precise, with artifact windows selected to the nearest second for exclusion, preserving as much of the WBV exposure data for analysis as possible. As an example, for train runs 30 to 35, 1.14% to 3.83% of the total seated exposure time contained artifact and was removed. The WBV exposure results were then recalculated to reflect the total seated exposure time based on ISO 2631-1 and 2631-5.

Figure 3 shows the plot of S_{ed} vs. the dominant VDV for each of the 35 train runs/jobs (VDV_{max}). A line of best fit was determined and is defined by the equation:

$$y = 0.0513x + 0.0134 \ (R^2=0.8893) \quad (1)$$

4. Discussion

The WBV exposures for the 35 train runs resulted in values for RMS and VDV whereby “health effects have not been clearly documented and/or objectively observed” (ISO 2631-1). The measures of career exposure risk (S_{ed}) according to ISO 2631-5 (2004) were at levels whereby there is a “low probability of an adverse health effect” (ISO 2631-5). The results and interpretations for health guidance were based on a "gold standard" WBV exposure assessment. This "gold standard" approach offered a measure of confidence that the WBV exposure experienced by locomotive engineers and conductors was as close as possible to their actual exposure. Part of the "gold standard" approach was to remove artifacts which was reported on by Cooperrider & Gordon (2008) and DiFiore et al. (2012). Page et al. (2016) set out to quantify the effects of removing or not removing artifacts and limiting the duration of WBV exposure data collection. Generally, VDV and S_{ed} were most affected and increased compared to the "gold standard" result as artifacts were not removed but decreased compared to the "gold standard" when exposure measurement duration was shortened. Weames et al. (2016) showed the effects of various WBV exposure data collection strategies for multi-modal machine operation. Compared to a "gold standard" approach, most alternate strategies led to results with enough difference to cause incorrect decisions on health guidance. Fleming et al. (2020) and Weames et al. (2021) continued investigating the effects of WBV exposure assessments that were alternate strategies compared to a "gold standard" approach for operation of locomotives and other industrial vehicles. The results of these two publications showed up to a 2444% difference in WBV exposure result values and many incorrect health guidance decisions. Cooperrider & Gordon (2008) assessed 19 WBV exposures and removed artifacts by comparing the seat pad accelerometer trace to the floor mounted accelerometer trace. When comparing accelerometer traces, a similar vibration profile indicates that the seat pan accelerometer excitation is due to vehicular sourced vibration (see Figure 4). However, dissimilar vibration profiles indicates that the seat pan accelerometer excitation is likely due to artifact, consistent with seat occupant movement (see Figure 5). At a minimum, accelerometer trace comparison can be reasonably effective for reducing artifacts due to movements of the seated occupant. It is possible that some artifacts, or even non-seated time could have been included in the WBV exposure data since the trace comparison method might not reveal all artifacts or non-seated time. The results of Cooperrider & Gordon (2008) were based solely on trace comparison while DiFiore et al. (2012) applied trace comparison and video records to confirm seated exposure time and the removal of artifacts.

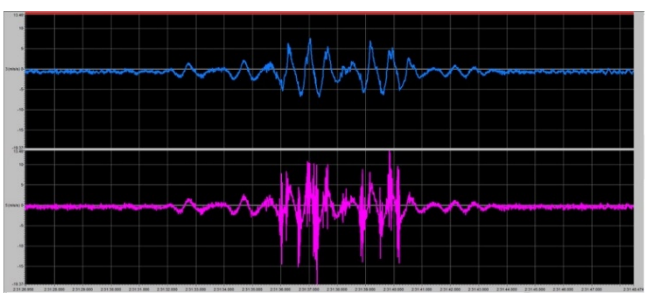

Figure 4: z-axis Accelerometer Traces Showing Vehicle Sourced Vibration (seat pan is top trace, frame is bottom).

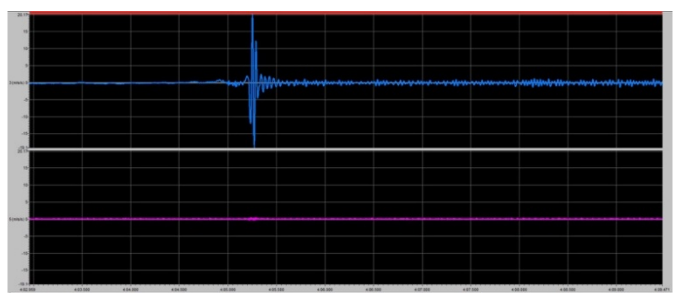

Figure 5: z-axis Accelerometer Traces During Seat Egress Causing Artifact (seat pan is top trace, frame is bottom).

Figure 3 demonstrated a reasonably linear relationship between VDV_{max} and S_{ed} (R^2=0.8893) suggesting that for the WBV exposure environment on board freight locomotives, these two metrics are in close agreement, as they also are each below their respective lower boundaries. Cooperrider & Gordon (2008) also reported a near linear relationship between VDV_{max} and S_{ed}, however they discussed that some VDV_{max} results were above the HGCZ lower boundary. It is suggested that this more robust data compilation and "gold standard" approach served to reduce the variance between VDV and S_{ed}.

5. Conclusions

This research presents a robust number of WBV exposure assessments for railroad industry train crew members incorporating a “gold standard” approach. The data is representative of actual train operations in many locations in the United States along with multiple makes/models/manufacture dates of locomotives and their seats. While there is some range of exposure among the data, RMS, VDV and S_{ed} values were all below the ISO 2631-1 and ISO 2631-5 lower boundaries of their respective HGCZ. The conclusion from this data compilation is that North American train crews are not at increased relative risk for the development of musculoskeletal disorders of the lumbar spine from WBV exposure on board freight locomotives operating in regular revenue service. Any additional WBV exposure assessments with a consistent "gold standard" approach can serve to add to the data presented here, and can provide continuing support for building safety knowledge in this important transportation sector.

Acknowledgments: The authors wish to thank the many train crews and railroad personnel with whom we have worked.

6. References

ANSI (2002). Mechanical vibration and shock-Evaluation of human exposure to whole-body vibration, part 1: General requirements (S3.18-2002). *American National Standards Institute*, N.Y.

Cooperrider, N.K. and Gordon, J.J. (2008). Shock and impact level on North American locomotives. *Journal of Sound and Vibration*, 318:809-819.

DiFiore, A., Zaouk, A., Durrani, S., Mansfield, N., Punwani, J. (2012). Long-haul whole-body vibration assessment of locomotive cabs. *Proceedings of the 2012 Joint Rail Conference [JRC2012]*, Philadelphia, PA, April 17-19.

Fleming, S., Weames, G.G., Page, G.B. (2020). Whole-Body Vibration Exposure– A Demonstration of the Importance of Artifact Removal, *Society for Industrial and Systems Engineering, 9th Annual Conference Proceedings*, Virtual Platform, September 17-18.

Federal Railroad Administration (FRA 1972). Human Factors Survey of Locomotive Cabs. *U.S. Department of Transportation, Report Number (FRA-OPP-73-1)*. Washington, D.C.

ISO 2631-1 (1997/2010). Mechanical Vibration and Shock –Evaluation of Human Exposure to Whole-Body Vibration (Part 1: General Requirements).

ISO 2631-5 (2004). Mechanical Vibration and Shock -Evaluation of Human Exposure to Whole-Body Vibration (Part 5: Method for Evaluation of Vibration Containing Multiple Shocks).

Johanning, et al. (2006). Whole-body vibration and ergonomic study of US railroad locomotives. *Journal of Sound and Vibration*, 594-600.

Larson, R., Raasch, C., Pierce, J. (2006). Measurement and evaluation of vibration exposure for locomotive crew members. *Proceedings of the First American Conference on Human Vibration*. NIOSH Publication No. 2006-140: 121-122.

Page, G.B., Fleming, S., Weames, G.G., Vanderpool, J., Frolich, J. (2010a). Rock and roll: perception and reality of whole-body vibration exposure under different service conditions. *Proceedings of the XXIInd Annual International Occupational Ergonomics and Safety Conference*, Tempe, AR, June 10-11.

Page, G.B., Fleming, S., Weames, G.G., Vanderpool, J., Frolich, J. (2010b). Whole-body vibration exposure at the seat pan: an investigation of jointed rail upon the locomotive cab. *Proceedings of the XXIInd Annual International Occupational Ergonomics and Safety Conference*, Tempe, AR, June 10-11.

Page, G.B., Fleming, S., Weames, G.G. (2010c). Data compilation and risk analysis for exposure to occupational physical factors for the North American railroad train crew: part II. *Association of Canadian Ergonomists 41st Annual Conference Proceedings*. Kelowna, BC, October 4-7.

Page, G.B., Weames, G.G., Fleming, S. (2015). Effect of track classification on whole-body vibration at the locomotive cab seat. *Proceedings of the 4th Annual World Conference of the Society for Industrial and Systems Engineering, Fort Lauderdale*, FL, October 19-21.

Page, G.B., Fleming, S., Weames, G.G. (2016). Sensitivity analysis of artifact removal and sampling period strategies upon whole-body vibration measurement. *Proceedings of the XXVIIIth Annual Occupatinal Ergonomics and Safety Conference,* Chicago, IL, June 9-10.

Weames, G.G., Fleming, S., Page, G.B. (2014). Locomotive train crew whole-body vibration exposure: an investigation of speed-restriction administrative controls. *Association of Canadian Ergonomists 45th Annual Conference Proceedings*, Montreal, QB, October 7-9.

Weames, G.G., Fleming, S., Page, G.B. (2016). Data Collection and Analysis Affects to the Results of Whole-Body Vibration Exposure for Machine Operators, *Association of Canadian Ergonomists 47th Annual Conference Proceedings*, Niagara Falls, ON, October 18-20.

Weames, G.G., Fleming, S., Page, G.B. (2021). Whole-Body Vibration Exposure Assessment – A Demonstration for the Need of a Gold Standard, *American Conference on Human Vibration, 8th Conference Proceedings*, Virtual Platform, June 23-25, 2021.