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Whole-body vibration and ergonomic study of US railroad locomotives

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Abstract

US locomotive operators have exposure to multi-axis whole-body vibration (WBV) and shocks while seated. This study assessed operator-related and ergonomic seating design factors that may have confounding or mitigating influence on WBV exposure and its effects. Vibration exposure was measured according to international guidelines (ISO 2631-1; 1997); ergonomic work place factors and vibration effects were studied with a cross-sectional survey instrument distributed to a randomly selected group of railroad engineers ($n = 2546$) and a control group; and during vehicle inspections. The survey response rate was 47% for the RR engineers ($n = 1195$) and 41% for the controls ($n = 323$). Results of the mean basic vibration measurements were for the x, y, z-direction and vector sum 0.14, 0.22, 0.28 and 0.49 m/s^2 respectively; almost all crest factors (CF), MTVV and VDV values were above the critical ratios given in ISO 2631-1. The prevalence of serious neck and lower back disorders among locomotive engineers was found to be nearly double that of the sedentary control group without such exposure. Railroad engineers rated their seats mostly unacceptable regarding different adjustment and comfort aspects (3.02–3.51; scale 1 = excellent to 4 = unacceptable), while the control group rated their chairs more favorably (1.96–3.44). Existing cab and seat design in locomotives can result in prolonged forced awkward spinal posture of the operator combined with WBV exposure. In a logistic regression analysis, time at work being bothered by vibration (h/day) was significantly associated with an increased risk of low back pain, shoulder and neck pain, and sciatic pain among railroad engineers. Customized vibration attenuation seats and improved cab design of the locomotive controls should be further investigated.

1. Introduction

In the European Union the risk of excessive whole-body vibration (WBV) exposure has been recognized and specific requirements regarding WBV exposure prevention have been introduced [1]. However, there is a paucity of information about the WBV exposure and working conditions of locomotive engineers in the generally available vibration and occupational health literature. One of the reasons is that this industry has been very reluctant in the past to study such issues and provide access to the work place. It appears that

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locomotive engineers and conductors are working in a unique environment with likely exposure to significant WBV and shocks depending on locomotive design, train speeds, and operational tasks [2,3]. In a recent epidemiological study of active North-American railroad (RR) engineers, the prevalence of serious type neck and lower back disorders was found to be nearly double that of a sedentary control group without such exposure [4], although the basic vibration levels appear to be lower compared to some road and off-road vehicles with high vibrations levels and back disorder risks. Ergonomic and seating conditions are important and possible modifying factors in an overall risk assessment of WBV exposure [5,6] and for musculoskeletal health in occupational medicine [7]. The goal of this study was the description and evaluation of cab and seating conditions in US built locomotives, including the subjective rating of seats and vibration effects by the locomotive engineers. Furthermore, the operational tasks that may be important and modifying factors in the risk assessment of WBV and prevention are reviewed.

2. Method

A self-administered 200-item standardized survey instrument was used to assess vibration effects, seating conditions and musculoskeletal disorders among a randomly selected subset of active US-American and Canadian RR engineers ($n = 2546$; out of total of 38,208) and a sedentary comparison group without rail-bound vehicle vibration exposure (New York State employed civil engineers, $n = 798$). The questionnaire was compiled from previously used and validated questions including the 'Standardized Nordic Questionnaire for the analysis of musculoskeletal symptoms', the British vibration exposure questionnaire developed by the Palmer and Griffin Group, University of Southampton and the Mount Sinai School of Medicine vibration survey [8–10]. The survey response rate was 47% for the RR engineers ($n = 1195$) and 41% for the controls ($n = 323$). The data was analyzed using SPSS statistical software (version 12.0, SPSS, Inc., Chicago, IL, September 2003). The association between the measures of exposure (vibration) and the measures of musculoskeletal pain (neck, lower back and sciatica pain) were tested by unconditional logistic regression. In addition, WBV was measured according to ISO 2631-1 (1997) in revenue-service locomotives ($n = 51$) during normal work-shifts. The seating conditions of a variety of in-service locomotives from different RR companies throughout the US RR system were inspected and typical operational tasks and body movements of locomotive operators were assessed by a trained medical observer.

3. Results

The results of the mean basic vibration measurements were for the x, y, z-direction and vector sum 0.14, 0.22, 0.28 and 0.49 m/s^2, respectively, based on full-shift WBV measurements ($n = 51$; duration approximately 4–16 h) of locomotives in revenue service in the US. The calculated SEAT ratios (seat/floor transfer function) indicated that the currently used seats did for the most part not reduce, but rather magnified the floor input vibration, particularly in the horizontal directions. Almost all of the calculated crest factor (CF), MTVV and VDV values were above the critical ratios given in ISO 2631-1, which suggests that relatively high and frequent irregular shocks on the seat level are common throughout routine work cycles (Table 1). The frequency resonance ranges of the measured locomotive seats were near the resonance range where the human spine shows the highest sensitivity (1–10 Hz).

The results of the survey showed that 75% of the RR engineers experienced "back pain" lasting more than 1 day in the year prior to completion of the survey, compared to 41% of the controls (Crude odds ratio (OR) = 4.32, 95% confidence interval (CI) 3.31–5.64). After statistical adjustment for demographic factors and non-job related vibration exposure, the adjusted OR remained essentially unchanged, 4.24 (95% CI 3.20–5.62). The adjusted OR for the occurrence of "sciatic pain" (a nerve root involvement) in engineers was 2.17 (95% CI 1.33–3.56). Other measures of back pain severity as well as neck and shoulder pain were also elevated among RR engineers. Within the RR group, higher job seniority was associated with a higher risk for persistent back pain.

Although the majority of currently used seats seem to have a back and foot support available (78–82%), there appears to be a lack of individual adjustment features, foot support (bracing device) and air cushioning devices (Table 2). In the survey, almost 2/3 of the engineers ($n = 1019$) complained about particular seat and

Table 1
Results of WBV measurements in US locomotives

Direction	Basic vibration values															
	a_w (m/s^2)			Vector Sum	Seat			Crest factor			MTVV/a_w			VDV/$a_wT^{1/4}$		
	x	y	z	av	x	y	z	x	y	z	x	y	z	x	y	z
n	51	51	51	51	43	43	43	51	51	51	51	51	51	46	46	46
Mean	0.13	0.23	0.29	0.48	1.39	1.21	0.97	15.98	10.84	14.44	7.32	6.12	5.66	1.87	1.66	1.69
Min	0.05	0.05	0.09	0.13	1.00	1.03	0.61	6.60	3.80	5.60	3.20	2.90	3.20	1.44	1.37	1.44
Max	0.72	0.71	0.50	1.44	2.19	1.51	1.56	67.26	28.07	45.74	26.16	14.38	10.29	4.27	2.48	2.09
SD	0.11	0.12	0.08	0.21	0.28	0.10	0.16	11.39	4.95	7.08	4.18	2.13	1.70	0.56	0.20	0.17
Mode	0.07	0.14	0.32	N/A	1.33	1.25	0.92	7.90	8.30	11.70	5.30	N/A	4.40	1.52	1.60	1.56

Table 2
Comparison of seat characteristics with the control group

	Locomotive engineer		Control		Significance level	
Check item (present/available)	Yes (%)	n	(%)	N	χ^2	p (χ^2)
(1) Arm rest?	82.3	1011	89.1	313	8.29	0.004
(2) Any type of back support?	78.7	1043	90.3	310	21.24	<0.001
(3) Adjustable back support?	30.5	1026	14.7	299	29.33	<0.001
(4) Air suspension or cushioning system?	11.1	1026	37.4	297	112.55	<0.001
(5) Round seat pad (toad stool) used?	20.0	985	23.1	303	1.36	0.244
(6) Any special foot rest or support available?	34.1	954	5.6	305	94.83	<0.001

cab design problems in the older and the newer "wide body" locomotives. Most frequently, the engineers complained about the cab lay out and seats (49%), followed by vibration (22%) and air conditioning/ventilation (11%). On a scale from 1 to 4 (1 = excellent, 4 = unacceptable), the RR engineers rated their seats mostly unacceptable regarding different adjustment and comfort aspects (3.02–3.51), while the control group rated their chairs more favorably (1.96–3.44).

In a logistic regression analysis, the variable 'time at work being bothered by vibration' (h/day) was significantly associated with an increased risk of low back pain, shoulder and neck pain, and sciatic pain among RR engineers (Table 3). Each hour being bothered by vibration increased risk of pain approximately 20%. This association was essentially unchanged after controlling for age, gender, race, smoking, vibration exposure in second job, spare time vibration exposure, seating characteristics (arm rests, any kind of back support, special adjustable lower back support, air cushion system, availability of footrest), engineers seat rating (comfort, adjustment, turning seat, arm rests, leg room), time sitting at work and employment duration. Similar associations were observed when examining all study participants, both RR engineers and controls.

RR employment is a proxy measure of lifelong exposure to WBV (mean RR job seniority was 22.4 years). Each 10 years of RR employment was associated with an additional 38% risk for back disorders at the measured vibration levels (data not shown).

4. Discussion and conclusion

This study demonstrated a close relationship of WBV exposure duration and neck and lower back problems in RR engineers. Although the mean basic vibration levels measured in the US locomotives appeared to be lower in comparison with some road and off-road vehicles with a known high risk for lower back disorders and other problems [11,12], the unique seating conditions, the locomotive operator's awkward body posture and likely the shock content of the vibration appeared to play an important factor in the overall assessment.

Table 3
Odds ratios of vibration, seating and other factors and musculoskeletal disorders among railroad engineers (Logistic regression analysis)

		Model 1[a]			Model 2[b]			Model 3[c]		
		OR[d]; CI[e] (Lower–Upper); p			OR; CI (Lower–Upper); p			OR; CI (Lower–Upper); p		
1	Back pain lasting more than 1 day in the past 12 months ($n = 1059$)	1.21	1.14–1.28	<0.001	1.21	1.14–1.29	<0.001	1.19	1.11–1.26	<0.001
2	Neck or shoulder pain lasting a day or more during the past 12 months ($n = 853$)	1.18	1.12–1.25	<0.001	1.19	1.12–1.25	<0.001	1.16	1.09–1.23	<0.001
		Following only for engineers who reported back pain lasting more than 1 day in the past 12 months:								
3	Sciatica pain at least once a week in past year ($n = 765$)	1.19	1.11–1.27	<0.001	1.19	1.12–1.27	<0.001	1.20	1.12–1.28	<0.001
		Model 4[f]			Model 5[g]			Model 6[h]		
		OR; CI (Lower–Upper); p			OR; CI (Lower–Upper); p			OR; CI (Lower–Upper); p		
1	Back pain lasting more than 1 day in the past 12 months ($n = 1059$)	1.19	1.12–1.27	<0.001	1.19	1.12–1.27	<0.001	1.19	1.12–1.27	<0.001
2	Neck or shoulder pain lasting a day or more during the past 12 months ($n = 853$)	1.16	1.10–1.23	<0.001	1.16	1.10–1.23	<0.001	1.16	1.10–1.23	<0.001
		Following only for engineers who reported back pain lasting more than 1 day in the past 12 months:								
3	Sciatica pain at least once a week in past year ($n = 765$)	1.19	1.11–1.28	<0.001	1.19	1.11–1.27	<0.001	1.19	1.11–1.27	<0.001

[a]Model 1: Time at work being bothered by vibration (h/day).
[b]Model 2: Adjusted for gender, racial origin (Caucasian vs. other), currently smoking (Y/N), vibration exposure second job (Y/N), spare time vibration exposure (min).
[c]Model 3: In addition, adjusted for seating characteristics (Arm rests, any kind of back support, special adjustable lower back support, air cushion system, availability of footrest) and engineers seat rating (comfort, adjustment, turning seat, arm rests, leg room).
[d]OR: Odds Ratio.
[e]CI: Confidence Interval, 95%.
[f]Model 4: In addition, adjusted for time sitting at work (h/day).
[g]Model 5: In addition, adjusted for employment duration (10 year increments).
[h]Model 6: In addition, adjusted for age.

Over the last century, it appears, there has been little change in basic concepts of locomotive cab and seat design in North America. For the most part any changes of the cab and seat design were driven by technical and operational requirements, structural/collision safety issues and vehicle design needs due to conversion from coal/steam to diesel-electric or electric power. Human factor requirements, operators' comfort and convenience, and in particular operator protection from harmful vibration and shocks appeared to have played a minor role in the current evolution of locomotive cabs, control stands and seating [13]. There are two basic locomotive cab design concepts in use in road or yard service locomotive engines: the 'Association of American Railroad (AAR) Control Stand' and the front consol in newer generation 'wide-body locomotives'. The yard locomotive engines are operated bi-directionally and the operator has to adjust and change the seating position frequently for the different driving directions (Figs. 1 and 2).

Locomotive engineers typically spend long hours inside the locomotive cab (8–12 h/day) and for most of the time are in a seated position (approximately 7 h/shift). During switching operations (yard) the seated body postures are frequently changed to view crew members and equipment resulting typically in awkward body postures during vibration and shock exposures (Fig. 1). In the traditional cab design (AAR control stands; used in 55% of the locomotives evaluated before 2002) the operator needs to reach forward to the left-sided hand controls at about an angle of 30–90°. This results typically in a twisting and bending motion of the

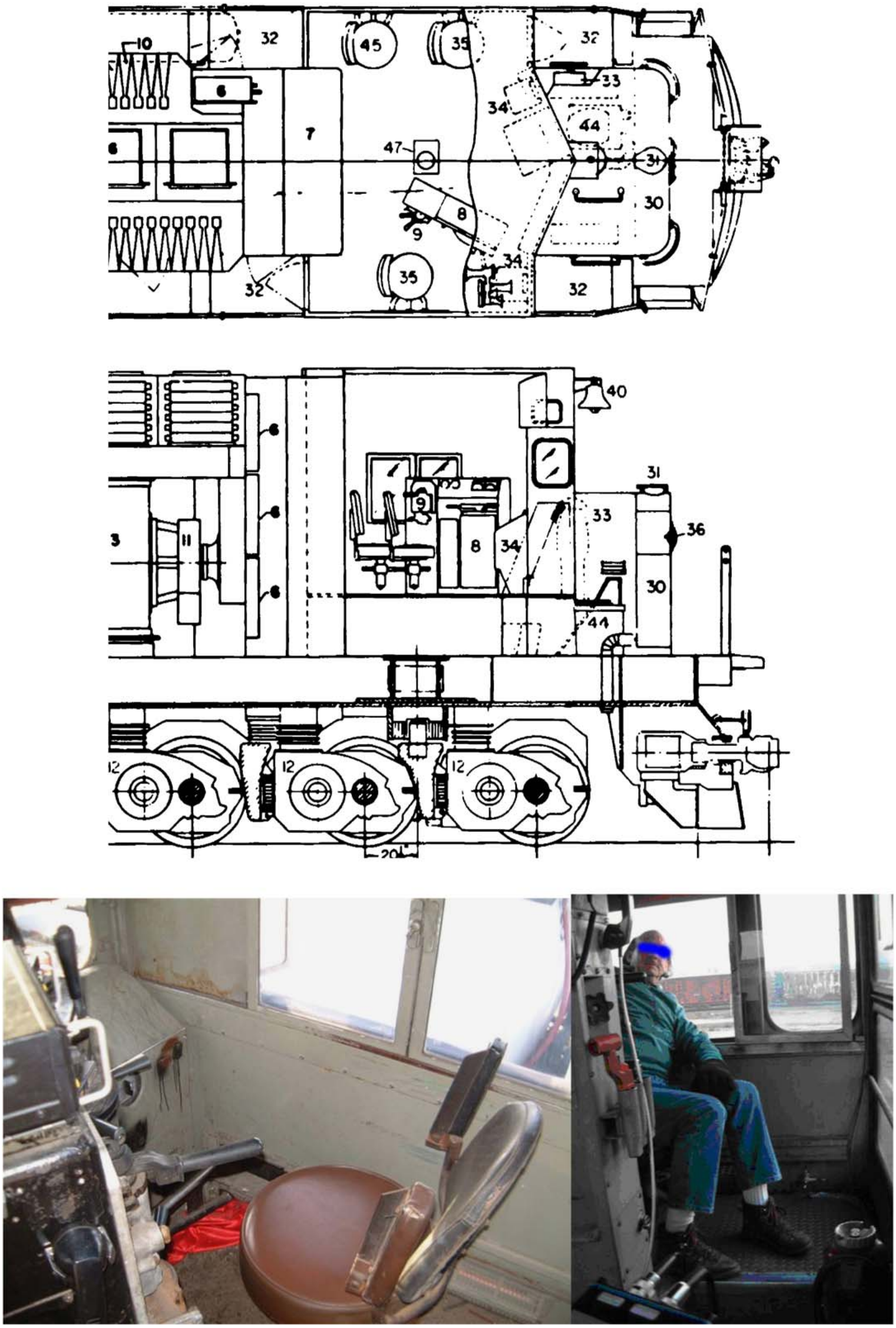

Fig. 1. Traditional cab and seat design (''American Standard Control Stand''), round toad stool, railroad engineer during yard switching.

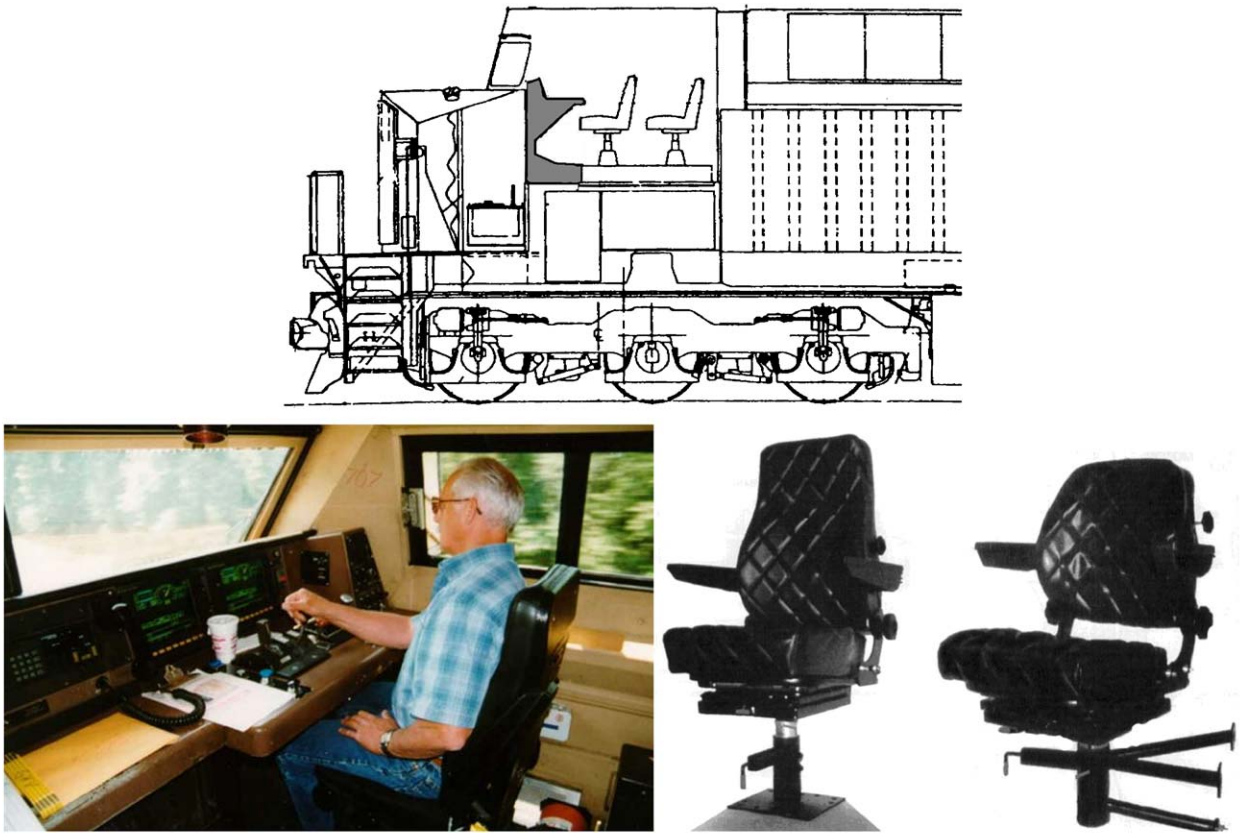

Fig. 2. Modern "wide body" locomotive cab and seat design.

operator's spine. In newer 'wide body locomotives' with the control console in front the locomotive operator has reduced requirements for upper body movements and reaching. However, engineers reported problems of proper seat adjustment for operators with large abdomens to reach the fixed controls, causing them to lean forward or sitting slightly sideways and thereby not adequately using the back support of the seat. Basic seat designs used in the locomotives ranged from the traditional round toad stool without any back or arm support, to seats with simple foam-on-wood seat pads, arm and back supports, and to modern seats with adjustable back, lumbar supports and arm rests. Few seats were equipped with a passive spring/damper mechanism. In any case, current cab and seat design in these locomotives were for the most part rated unfavorably and often considered inadequate by locomotive engineers.

Occupational musculo-skeletal problems of locomotive engineers and in particular disorders of the spine were recognized earlier in Europe and North America [14–17], however no vibration exposure information and cab/seat design details were reported. The role of seating posture, awkward positioning and seat/cab adjustment features in the overall vibration exposure risk assessment generally appears to be important, although few studies have specifically addressed these vibration aspects. The important role of the driver's posture leading to musculoskeletal problems has been emphasized in an earlier ergonomic review [18]. Helicopter operators with relatively low and similar vibration levels as described in the rail bound vehicles (locomotives) were also found to have a high rate of back (including neck) disorders, possibly due to combined effects of vibration and forced awkward spinal posture (asymmetric) because of seat and cab design features [11,19–21]. In this study and similar reports no exact postural measurements of operators have been reported which may provide additional information for a WBV and postural risk assessment. However, it is assumed among experts that a vehicle operator in a relaxed seating position without twisting and bending of the spine (symmetric) is at a lower risk of spinal stress and longtime injury. Future studies should focus on the real-time measurement of the locomotive engineer's body posture (back and neck/shoulder) during a typical work-shift and WBV measurement and compare the results to other vehicle drivers. In the meantime, preventive engineering and interventions utilizing current technology and scientific standards appear prudent to reduce adverse WBV effects on locomotive operators [22]. Customized vibration attenuation seat and cab design of locomotives and improved operator's task management should be further investigated.

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