Whole Body Vibration and Back Disorders Among Motor Vehicle Drivers and Heavy Equipment Operators

A Review of the Scientific Evidence

Report to:

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Executive Summary

The purpose of this review was to determine whether there is support for a causal link between exposure to whole body vibration and back disorders in vehicle operating occupations.

The review was completed in three steps. We searched the scientific literature using electronic databases (Medline, EMBASE, NIO SHTIC, Ergoweb, and Arcline) and reference literature, then sorted the literature for relevance and topic. The selected scientific studies were reviewed using standard epidemiological criteria, looking for consistency between studies, strong associations unlikely to be due to chance or confounding, increases in response with increases in exposure, and plausible temporal and biological relationships.

Forty epidemiological studies of the association between back disorders and vehicle operation jobs were selected for detailed review. The risk was elevated in a broad range of driving occupations, including truck drivers, earth moving machine operators, power shovel operators, bulldozer operators, forklift drivers, crane operators, straddle carrier operators, agricultural workers, tractor drivers, bus drivers, helicopter pilots, subway operators, reindeer herders, and vehicle drivers not otherwise specified. The risk estimates indicated strong associations, especially in the best designed studies. Risks increased with employment duration, as well as with vibration duration and dose, and to a lesser extent, intensity. Experimental studies in humans and animals support the biological plausibility of a relationship.

Twenty-five studies of vibration exposure levels indicated that vehicles used in the jobs named above are likely to expose workers to vibration levels in excess of exposure standards referenced in the new Occupational Health and Safety Regulation of the Workers' Compensation Board of British Columbia.

The data support a causal link between back disorders and both driving occupations and whole body vibration. Numerous back disorders are involved, including lumbago, sciatica, generalized back pain, and intervertebral disc herniation and degeneration. Elevated risks are consistently observed after five years of exposure.
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1. Purpose

The purpose of this report is to review and evaluate the scientific literature to determine whether there is support for a causal link between exposure to whole body vibration (hereafter, also simply referred to as “vibration”) and back disorders, with specific reference to occupations involving the operation of heavy equipment or driving motor vehicles. For any link found, the report will indicate the nature of the back disorders, and the duration of exposure that is associated with increased risks.

2. Methods

The review was completed in three steps: searching and collecting the scientific literature; sorting the literature for relevance and topic; and review of the evidence.

2.1 Literature Search

The literature retrieval was begun with a search of several electronic databases:

- Medline, which abstracts most of the international biomedical literature, searched from 1966 to November 1998;
- EMBASE, which abstracts 3,500 international journals with an emphasis on the pharmaceutical sciences, searched from 1988 to November 1998;
- NIOSHTIC, a bibliographic database focusing on occupational health and safety, including historical references, searched to November 1998;
- Ergoweb, an on-line catalogue of 3,288 references from 1920 to 1995 related to ergonomic issues; the company was established by the Ergonomics and Design group at University of Utah’s Department of Mechanical Engineering; and
- Arbline, from the library of the National Institute for Working Life in Sweden, with articles from 1980 to November 1998.

Text word searches of article titles and abstracts were conducted using the following terms: whole body vibration, WBV, vibration, back, spine, low back, lumbar, disc, vertebral, intervertebral, spondylitis, spondylolisthesis, sciatica, injury, skeletal stress, driver, driving, forklift, coach, crane, pilot, operator, operating, machine, vehicle, tractor, train, subway, heavy equipment, motor vehicle, heavy equipment. Boolean operators and restriction to articles on humans were used to reduce the search results to those articles possibly relevant.

The web pages of several ergonomics societies were searched for information on seminars and conference proceedings related to occupation and back pain: the Human Factors Association of Canada; the Ergonomics Association of the UK; Human Factors and Ergonomics; and the International Ergonomics Association.

In addition, we used the reference lists of the following reports to find citations:

- “Musculoskeletal Disorders (MSDs) and Workplace Factors A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity, and Low Back” edited by Bruce P. Bernard, National Institute for Occupational Safety and Health, Cincinnati, O H, July 1997; and
Finally, the literature gathered was examined for references which had not been found by the above methods. Our selection of articles aimed to be inclusive, so that exclusions would occur after the literature had been retrieved and examined for relevance. In total, over 400 articles, monographs, and books were selected for library retrieval.

2.2 Literature Selection

The literature gathered was then sorted into the following categories:
1. epidemiological studies of the relationship between driving or equipment operation and back disorders;
2. epidemiological studies of back disorders in multiple occupations;
3. experimental studies of the effects of whole body vibration on the back;
4. studies of factors other than whole body vibration which are associated with back disorders and might therefore confound associations between vibration exposure and back disorders;
5. measurements of whole body vibration exposures of drivers and equipment operators; and
6. other articles about the back, whole body vibration, or occupations, but not relevant to the question at hand.

The first three categories represent the literature examining the relationship between exposures and health effects, however the quality of the information in each category was not considered equal. Category 1 represents epidemiological studies of working populations in the occupations of interest. Because the populations studied represent real workforces with the usual range of ages, health, personal characteristics, and working conditions, these studies were considered the best possible to answer the question posed. Category 2 also studied real working populations, however the range of occupations included meant that drivers and equipment operators might be grouped within large categories such as "transportation industry" or "construction industry", which would also include employees who were not drivers or equipment operators. Therefore the potential for misclassification of vibration/driving exposure was high. Category 3 represents experimental studies. Although experimental data can provide the most convincing evidence of a cause and effect relationship between an exposure and a disease, in the experimental studies we retrieved, vibration exposures were produced in an artificial setting, the study subjects were most often small groups of healthy, young, male volunteers, and the outcomes measured were not back disorders, but acute changes in the spine or the back muscles or subjective acute pain responses. These studies are mainly valuable for establishing biological plausibility. Because more than 40 studies were found in category 1, the category considered most likely to directly address the question at hand, studies in categories 2 and 3 were not considered in detail in this review.

Literature in categories 1, 2, and 4 was reviewed in order to develop an understanding of factors other than whole body vibration which are associated with back disorders. If these factors were also related to the jobs or the personal characteristics of drivers and equipment operators, they might alter the relationship between whole body vibration and these occupations. It would be important then to control or adjust for these "confounding factors" in the category 1 studies.
Literature in category 5 was included because most of the epidemiological studies in category 1 did not include measurements of whole body vibration in driving and equipment operating occupations. The "exposure" was often simply the job itself, or the duration of employment in the job. A separate literature exists examining the levels of whole body vibration exposure from a variety of motor vehicles and heavy equipment. This literature was reviewed in order to develop an understanding of the levels of exposure experienced by drivers and equipment operators, and to compare these levels to existing exposure standards.

Studies which fell into categories 1, 2, 4, and 5, but whose methodology could not be understood either because it was poorly described or written in a language other than English were not included in our review.

2.3 Evaluation of the Literature

In order to evaluate whether epidemiological evidence of an association between an exposure and a health outcome is likely to be causal, epidemiologists usually weigh the evidence using Hill's [1965] criteria. Although there are caveats for many of Hill's criteria [Rothman, 1986], 5 of the original 9 are commonly used as the basis for making inferences about causality. These are listed in order of importance (most to least) below.

- **Consistency of the association.** Is the association found repeatedly in studies of different populations, in different conditions, with different designs?
- **Strength of association.** How high is the risk in exposed populations compared to unexposed populations (i.e., the relative risk)? Is the relative risk high enough to exclude chance or confounding as possible explanations?
- **Dose-response.** Does the effect increase in a predictable way, as the exposure intensity, duration, or dose (intensity times duration) increase?
- **Temporal relationship.** Does the effect appear after the exposure? Is there usually an induction period between first exposure and disease onset, and if so, is the timing of the disease plausible in relation to the exposure?
- **Plausibility.** Is the association plausible given the basic science and clinical knowledge about the disease?

Our review of the literature considered these questions, and weighed the evidence. The evaluation was conducted blind to the results of other reviews of the epidemiological literature on whole body vibration and back disorders.
3. Results

3.1 Potential Confounders: Factors Other than Vibration Related to Back Disorders

Most studies examining factors associated with back disorders in the general population and working groups have examined correlates of subject-reported back pain or symptoms, using questionnaires. A few have examined more objective outcomes, including lumbar disc degeneration and herniation [Bovenzi and Betta, 1994; Bovenzi and Zadini, 1992; Dupuis and Zerlatt, 1987; Videman et al., 1990; Wiikery et al., 1978]. Risk factors which have been consistently found to be related to back pain and back disorders include the following:

7. **age**
   - Backman, 1983; Derriennic et al., 1994; Dupuis and Zerlatt, 1987; Heliövaara et al., 1991; Holmstrom et al., 1993; Kompier et al., 1987; Leigh and Sheetz, 1989; Liira et al., 1996; Magora, 1970; Petrovic and Milosevic, 1985; Roncarati and McMullen, 1988; Riihimaki et al., 1989b; Undeutsch et al., 1982; Wiikery et al., 1978;

8. **working postures**
   - Biering-Sorensen, 1983; Bovenzi and Betta, 1994; Bovenzi and Zadini, 1992; Burdorf et al., 1991; Damlund et al., 1986; Frymoyer et al., 1983; Holmstrom et al., 1992; Hrubec and Nashold, 1975; Keyserling et al., 1988; Liira et al., 1996; Masset and Malchaire, 1994; Riihimaki et al., 1989b; Rosecrance et al., 1992; Troup and Videman, 1989; Xu et al., 1997;

9. **repeated lifting and heavy labour**
   - Clemmer et al., 1991; Damlund et al., 1986; Derriennic et al., 1994; Frymoyer et al., 1980; Frymoyer et al., 1983; Harber et al., 1985; Leigh et al, 1991; Leigh and Sheetz, 1989; Liira et al., 1996; Magnusson et al., 1996; Masset and Malchaire, 1994; Saraste and Hultman, 1987; Thorbjörnsson et al, 1998; Troup and Videman, 1989; Videman et al., 1990; Walsh et al., 1989; Xu et al., 1997;

10. **smoking**
    - Biering-Sorensen et al., 1989; Frymoyer et al., 1980; Frymoyer et al., 1983; Heliövaara et al., 1991; Leigh and Sheetz, 1989; Lindal and Stefansson, 1996; Liira et al., 1996; Pietri et al., 1992; Roncarati and McMullen, 1988; Riihimaki et al., 1994; Troup and Videman, 1989;

11. **previous back pain**
    - Biering-Sorensen, 1983; Biering-Sorensen et al., 1989; Froom et al., 1987; Heliövaara et al., 1991; Riihimaki et al., 1989b; Riihimaki et al., 1994; Roncarati and McMullen, 1988; Troup et al., 1981;

12. **falls or other injury-causing events**
    - Biering-Sorensen, 1985; Clemmer et al., 1991; Damlund et al., 1986; Leigh et al, 1991; Troup and Videman, 1989;

13. **stress-related factors including job satisfaction and control**
    - Derriennic et al., 1994; Heliövaara et al., 1991; Holmstrom et al., 1993; Roncarati and McMullen, 1988; Svensson and Andersson, 1989; Thorbjörnsson et al., 1998; Troup and Videman, 1989; Xu et al., 1997; and
14. **Body condition and morphology including weight, height, physical condition, and body type**

[Hrubec and Nashold, 1975; Nordgren et al., 1980; Riihimaki et al., 1989; Roncarati and McMullen, 1988; Ryden et al., 1989; Troup and Videman, 1989; Undeutsch et al., 1982].

Most of these factors are biologically plausible as predictors of back disorders. Smoking is perhaps surprising; postulated mechanisms include the possibility that smokers have physical characteristics which make them susceptible to back disorders, or that smoking induces hormonal or other physical changes which increase back problems [Frymoyer et al., 1980]. Whether stress is a causal factor or a result of back pain is still unknown [Burdorf and Sorock, 1997]. Some prospective studies suggest it may be a predictive factor, though the mechanism involved remains elusive [Heliövaara et al., 1991].

A number of other factors have also been found to be related to back pain, but the results are either inconsistent from study to study, or the association has been found only rarely: education [Magora, 1970; Reinsbord and Greenland, 1985; Roncarati and McMullen, 1988]; marital status (no consistent relationship to a specific status) [Biering-Sorensen et al., 1989; Hrubec and Nashold, 1975; Reinsbord and Greenland, 1985; Ryden et al., 1989]; gender (no consistent relationship to one sex or the other) [Lindal and Stefansson, 1996; Magora, 1970; Reinsbord and Greenland, 1985; Roncarati and McMullen, 1988]; fatigue [Svensson and Andersson, 1989; Troup and Videman, 1989]; coffee consumption [Roncarati and McMullen, 1988]; and rural residence [Hrubec and Nashold, 1975].

### 3.2 Epidemiological Studies of the Association between Back Disorders and Driving or Equipment-Operating Occupations

Table 1 summarizes the characteristics and results of studies considered most relevant to the issue of whether there is an association between whole body vibration exposure and back disorders in driving/equipment operation professions. The quality of each study was evaluated based on the following characteristics listed in the table.

- **Study Design**: Most of the studies were cross-sectional, meaning that the exposure and the outcome were measured at the same time. These designs are less desirable because it is difficult to ascertain the timing of any exposure-disease relationship, and because both existing and new disease cases are mixed together. Two studies used a case-control design, which compares exposures among individuals with and without a disease. They offer the opportunity to select cases and isolate exposure timing in a clearer way, however assessing certain types of past exposures can be problematic. Nine studies included a cohort design, which compares disease incidence in exposed and unexposed populations. This design is considered the best observational epidemiological design.

- **Study Subjects and Controls**: To allow inferences about the rate of back disorders, it is best to include a control group that is as similar to the subject group as possible, in every way except vibration or driving exposure. Studies were required to have a control group to be included in Table 1; some used “internal” controls, meaning they made comparisons within a set of subjects that had varying jobs or exposure levels. In general, it is preferable to have large numbers of study subjects (most studies had hundreds, some thousands of subjects). Many of the studies included only males.

- **Confounders**: As described in the previous section, these are the factors, other than whole body vibration, that are related to back disorders. They have the potential to distort a study’s findings if they are also related to driving or vibration exposure. Some studies, especially the early cross-
sectional studies controlled for no or few confounders. Many of the more recent studies were able to control for a wide range of potential confounding factors. It is not necessarily appropriate to control for every known risk factor. For example, although prior back pain is a strong predictor of new episodes, controlling for this risk factor may obscure real associations, if the occupational factor of interest led to the initial disease.

- **Exposure Measurements**: In many of the studies, “exposure” was simply a specific driving or equipment operating job. In some cases, this was further elaborated by considering the duration of employment in these jobs. Job histories are known to be quite accurately reported. Some recent studies have included self-reports of “vibration exposure” by the study subjects. This subjective measure of exposure is likely to be somewhat less reliable than job information because each subject may have a different internal scaling of vibration levels. Some studies included measurements of vibration intensity (in units of vibration acceleration, e.g., m/s² or dB) and vibration dose (in units of time multiplied by vibration acceleration squared, i.e., year x m²/s⁴). Although these are not likely to be measurements of the actual equipment used by each subject, they have the advantage of being objective measures of the exposure of interest.

- **Outcome Measurements**: In most studies the disease outcome was self-reported back pain, lumbago, sciatica, or back trouble. These are subjective measures, but given that pain reporting is the basis for diagnosis, it is likely to be reliable. The questions used to elicit pain reports, and the case definitions, differed from study to study, so it would not be reasonable to compare incidence or prevalence percentages across studies, but comparisons within studies are appropriate. A number of studies used more objective measures of back disease, including herniated lumbar or cervical intervertebral discs, deviations of the lumbar spine, sickness absence or disability due to back disorders, and hospitalization records. A number of studies reported only the proportion (in %) of subjects and controls with the disease in question. Incidence indicates the new cases in a given time period as a proportion of the population; it is a direct measure of disease “risk”. Prevalence indicates the existing cases in a given time period as a proportion of the population, and is related to both the incidence and duration of the disease. These simple proportions were rarely controlled for confounding. Most studies used a ratio of disease incidence or prevalence in subjects versus controls as the measure of association between the exposure and the outcome, e.g., incidence density ratios, odds ratios, standardized hospitalization ratios, prevalence ratios. We called these ratios “relative risks” (RRs) in Table 1. A RR of 1 indicates that the disease rate is the same in subjects and controls; a RR greater than 1 indicates a higher disease rate in exposed subjects than in controls. RR calculations usually give an opportunity to control for confounding. Most of the studies included statistical tests to determine whether the results might be due to chance. These tests were sometimes reported as “p-values”; when these are less than 0.05, the result is considered statistically significant. Confidence intervals around a RR are another method of statistical testing. If a confidence interval does not include “1”, the RR is considered statistically significant.

Based on the design characteristics described above, the studies were assigned a ranking from (A), well designed studies, to (C), studies with a number of deficiencies, considered useful mainly as contributors to the overall evidence. These rankings appear in the Author (year) column of Table 1. The evaluation of the evidence from the epidemiological studies appears below, based on Hill’s [1965] criteria.
3.2.1 Consistency

The 40 studies reported in Table 1 all allow comparison between a subject group and controls. In all but one of these studies, elevated risks of back disorders (RR > 1 and/or higher percent prevalence in subjects than controls) were shown for driving or equipment operating occupations and/or vibration exposure.

Four studies found some risks which were not elevated. In the cohort study of Bongers et al. [1988a], the risk of a sickness absence of greater than 28 days or disability pension due to all back disorders was only slightly elevated in all crane operators, and not elevated in crane operators with at least 5 years of work experience, however the risks of herniated lumbar disc and discopathy were elevated for both of these work categories. The cross-sectional study by Walsh et al. [1989] found no elevated risks for back pain in women driving more than 4 hours per day, but did for men. This study also found no elevation in lumbago risk for men or women driving a truck, tractor or digger in the last year, but did find elevated risks for unremitting back pain. In the cross-sectional study by Heliövaara et al. [1991], no elevations in risk were observed for sciatica, and the risk of back pain was only slightly elevated and virtually disappeared when the complete list of confounders was included in the analysis. Finally, in the cohort study of Boshuizen et al. [1992], no elevation in risk of back pain or lumbago was found for vibration doses received 5 years or more prior to the onset of pain, but the risk was clearly elevated for more recent vibration exposures.

Despite some negative results within these 4 studies, elevated risks were demonstrated in 39 studies examining many driving and equipment operating professions, with a variety of exposure measurement methods, and for a range of back disorders. Epidemiologists would consider the degree of concordance remarkable.

3.2.2 Strength of Association

In 17 of the 30 studies that measured relative risks, RRs were greater than 2.0. All but one of the 13 studies with a study design ranked (A) found RRs greater than 2.0; the vast majority of these results were also statistically significant. The fact that the RRs tended to be more consistently high in the best quality studies is not surprising, since good study designs are more likely to characterize the relationship between exposure and disease without misclassification, and therefore more easily detect elevated risks where they do exist.

The importance of a relative risk of 2.0 or greater is two-fold. First, confounding by other uncontrolled risk factors is considered unlikely to explain relative risks of this magnitude. Second, when considering disease compensation, the probability that a disease is attributable to a given exposure (the "attributable risk", AR) is often considered important. Attributable risk is calculated by the following formula:

\[ AR = \frac{RR - 1}{RR} \]

A RR greater than 2.0 means the probability that the disease is due to the exposure is greater than 0.5, i.e., more probable than not.

3.2.3 Dose-Response
Twelve studies, including 9 of the best quality studies, allowed some consideration of whether an increase in exposure leads to increased risk of back disorders. The methods used included consideration of the duration of employment in driving/equipment operating jobs, duration of exposure to vibration, and intensity and dose of vibration exposure.

In most studies examining the trend in back pain, sciatica, and herniated discs with years of employment or years of vibration exposure, the risk and/or prevalence increased with duration [Brendstrup and Biering-Sorensen, 1987; Bongers et al., 1988a; Bongers et al., 1988b; Boshuizen et al., 1990b; Bovenzi and Zadini, 1992; Chernyuk, 1992; Pietri et al., 1992; Bovenzi and Betta, 1994; Masset and Malchaire, 1994]. Bongers et al. [1988a] found no trend in risk when all back disorders were combined, but did find an increase in risk for herniated discs and discopathy with at least 5 years of employment. Most of these studies identified increases in risk after 5 years of employment. Brendstrup and Biering-Sorensen [1987] found increased risks with as little as 3 to 5 years of employment, and Boshuizen et al. [1990a] found increases with 0 to 5 years of employment, but Bongers et al. [1988b] found no increase in risk with less than 5 years of employment. Increasing risks of back pain, sciatica, discopathy, herniated disc, and disc degeneration were observed in these studies, which included examinations of forklift drivers, crane operators, agricultural workers, bus drivers, tractor drivers, and industrial vehicle drivers.

Studies examining hours of driving per week [Pietri et al., 1992] and working days per year [Nayha et al., 1991], but not total duration of exposure, found weaker positive trends with increases in working time.

Two studies found that risk, especially for back pain, increased with up to 15 years of exposure then decreased after that [Bongers et al. 1988b; Bovenzi and Zadini, 1992]. This may be due to a "survivor effect", i.e., those who remain in the profession may be those who are less susceptible to back disorders. A numbers of authors commented on evidence in their study group that susceptible individuals leave driving jobs [Backman, 1983; Brendstrup and Biering-Sorensen, 1987; Bongers et al., 1988b; Netterstrom and Juel, 1989; Boshuizen et al., 1992].

Increasing intensity of vibration exposure was also related to increases in back disorders, though not as strongly or consistently as years of exposure [Boshuizen et al., 1990b; Bovenzi and Zadini, 1992; Chernyuk, 1992; Bovenzi and Betta, 1994]. This difference in effect may indicate that duration of exposure is a more important predictor of back disorders than intensity. However, it might also reflect the fact that intensity of exposure was estimated from measurements on representative vehicles rather than the ones used by the study subjects. Duration of exposure measurements were subject specific.

Vibration dose, which includes the effect of both intensity (squared) and duration of exposure, was examined in four studies [Bongers et al., 1990; Boshuizen et al., 1990a; Boshuizen et al., 1990b; Bovenzi and Zadini, 1992; Bovenzi and Betta, 1994]. Increasing risks of back disorders with dose were observed in these studies, though the studies by Bovenzi and Zadini [1992], and Bovenzi and Betta [1994] showed somewhat less consistent increases.

3.2.4 Temporal Relationship
Both the case-control and cohort study designs were able to ascertain that the vibration or driving exposures preceded the development of disease [Kelsey and Hardy, 1975; Brendstrup and Biering-Sørensen, 1987; Heliövaara, 1987; Bongers et al., 1988a; Bongers et al., 1988b; Netterstrom and Juel, 1989; Boshuizen et al., 1990a; Boshuizen et al., 1990b; Pietri et al., 1992; Riimaki et al., 1994, Jensen et al., 1996; Thorbjörnsson et al., 1998].

Only one study addressed the issue of a possible induction or latent period. Boshuizen et al. [1992] found that exposures within five years of diagnosis were strongly related to back pain including lumbago, but exposures more than 5 years previously were not. Whether this result is generalizable requires further investigation.

3.2.5 Plausibility

The biological plausibility of a relationship between whole body vibration exposure and back disorders is best addressed by experimental studies of humans and animals. Wilder and Pope [1996] recently conducted an extensive review of over one hundred such studies. Their review describes the following:

- the magnitude of vibration transmitted to the human spine is greatest at resonant frequencies from 4.5 to 5.5 Hz and from 9.4 to 13.1 Hz;
- bending and rotating postures (the latter are often assumed by tractor, heavy equipment, crane, and forklift operators) increase vibration transmission;
- sitting postures, which rotate the pelvis backwards and flatten the lumbar spine, may amplify vibration transmission to the spine, and increase movement of the sacro-iliac joint;
- muscles are fatigued by vibration exposure, and oxygen consumption increases;
- movement of the intervertebral discs causes stress on the annular fibres;
- vibration increases pressure within the discs;
- vibration causes mechanical forces which reduce the “fatigue life” of a material (biological or man-made); and
- herniated discs were produced in cadavers subject to vibration.

For the purposes of this review, another consideration in the plausibility argument is whether motor vehicles and heavy equipment do in fact produce vibration, and if so, at what intensity and frequency. This is the subject of the next section.

3.3 Studies Reporting Whole Body Vibration Exposures in Driving or Equipment-Operating Occupations

Table 2 summarizes the exposure levels reported in 25 studies of whole body vibration generated by vehicular motion. It includes studies of mining equipment, locomotives, subway trains, heavy equipment, forestry equipment, agricultural equipment, buses, trucks, vans, cars, and forklifts, as well as cranes, snowmobiles, and helicopters. The table indicates the industry and study conditions, the measurement method, the type of vehicle, the vibration levels and dominant frequencies, compliance with standards, information about peaks or jolts, and factors increasing vibration levels.
The following sections provide a brief overview of the methods used to measure vibration, the exposure standards that exist, and a comparison to current exposure standards of the vibration levels measured in various equipment types.

3.3.1 Measuring Vibration

The majority of studies were conducted under “normal” or “typical” operating conditions. Most studies measured vibration acceleration (intensity) in 3 axes (Z – vertical; X – front to back; and Y – side to side). Howat [1978] restricted measurements to the Z-direction, the axis considered the most significant contributor to vibration exposure in most situations. Measurement details were not reported by Barbieri et al. [1995], Holmlund and Lundstrom [1999], Netterstrom and Juel [1989], or Suvorov et al [1996]. Measurements were generally taken at the “seat-operator interface” using triaxial accelerometers, which transduce vibration forces into acceleration measurements. In addition, some investigators took measurements at the seat back or at the floor surface.

Measurements were usually reported in m/s² (units of acceleration). A few studies reported in decibels, in which the measured acceleration is expressed as a ratio to a reference acceleration level, normally 10⁻⁶ m/s². Suvorov et al. [1996] appear to have used a reference level of 2.5 x 10⁻⁶ m/s².

3.3.2 Vibration Standards

Many studies compared the vehicle vibration levels to the whole body vibration standard of the International Standards Organization (ISO 2631/1 Evaluation of Human Exposure to Whole-body Vibration). This standard is referenced in the new Occupational Health and Safety Regulation of the Workers’ Compensation Board of British Columbia, section 7.25. Some authors reported the probability of a worker being subjected to exposures above the ISO standard, or the percentage of observations which exceeded the standards. Other authors reported the time it would take to exceed the standard.

The ISO standard differs for the three vibration axes, since the critical frequencies with respect to health are different for the vertical (Z; 4-8 Hz) and the two horizontal axes (X, Y: 1-2 Hz). Unless averaged (as described next), each axis is compared individually to its respective ISO 2631 standard. Alternatively, the ISO 2631 standard suggests averaging the three axes, after applying the ISO’s standard weighting to the individual measurements at each frequency (related to the expected health effects), then root-mean-square averaging to create the “vector sum”. Several investigators report the vector sum, which is then compared directly to ISO recommendations for the Z-axis at 4 to 8 Hz.

The ISO provides three exposure standards:
- the level at which “fatigue decreases proficiency” (“FDP”);
- the “exposure level” (“EL”; set at 2 x the FDP), defined as one-half the exposure which results in pain or voluntary withdrawal of subjects in experimental tests; and
- the “reduced comfort boundary” (“comfort standard”; set at the FDP/3.15).

The 8-hour FDP for the z-axis at 4 to 8 Hz is 0.315 m/s², the standard against which a vector sum would be compared.
Crest factors are a way of determining whether there are peak accelerations greatly in excess of the average levels. They are calculated as the peak acceleration divided by the root-mean-square average over a one-minute measurement duration. By definition, a sinusoidal vibration has a crest factor of 1.41 (the square root of 2). The use of root-mean-square measurements such as the ISO standards should be limited to situations where the crest factor is less than 6, or the measurement is likely to underestimate the true vibration exposure. Some authors have also reported the presence of jolts and shocks as a way of accounting for the additional effects these forces would have beyond the root-mean-square averaged acceleration levels.

The British standard (BS 6841) uses a “vibration dose value” (VDV) which averages after raising the acceleration measurements to the fourth power. This method more heavily weights higher acceleration levels, which are considered to have a proportionately greater effect on health. This method is considered optimal where crest factors exceed 6. In situations with crest factors below approximately 6, the VDV can be estimated from the RMS value:

$$e^{VDV} = 1.4 \times (\text{RMS value})(\text{duration})^{0.25}$$

In higher crest factor situations, the VDV is estimated directly from the frequency weighted acceleration time history. The units are m/s^{1.75}. The British standard states that VDV’s in the region of 15 m/s^{1.75} will usually cause severe discomfort; this is considered an action level.

3.3.3 Comparison of Vehicle Vibration Measurements to Exposure Standards

In 22 of the 25 measurement studies reported in Table 2, vehicle vibration levels exceeding the ISO 2631 FDP 8-hour standard were measured. Although in many studies at least some measurements were below this exposure standard, only 7 studies reported average levels for individual vehicles which were below the standard.

Redmond and Remington [1986] found 4 of 12 mining vehicles to have a zero probability of exceeding the higher ISO 2631 limit, the EL: blast hole drills, motor graders, shovels and draglines, and bridge conveyors. In Netterstrom and Juel [1989], measurements among bus drivers were below the FDP, but above the comfort limit. It is interesting to note that this study still found elevated risks of herniated lumbar disc among bus drivers (Table 1). Boshuizen et al. [1990a] reported that of the 11 vehicles they measured, a car and a combine harvester had levels below the FDP, but above the comfort standard. Bovenzi and Zadini [1992] reported that 4 of 6 types of buses had levels above the FDP; the other 2 had lower levels, though still above the comfort standard. Burdorf and Swuste [1993] measured vibration acceleration in 24 vehicles. Of these, only one forklift (of 6) had levels below the FDP, but again above the comfort standard. Suvurov et al. [1996] measured consistently low vibration levels in tractor drivers, bulldozer operators, open cast mine excavator operators, and drill rig operators. These results do not agree with those of other studies examining the same types of equipment, perhaps because this study appeared to use data summarization methods that differed from the ISO 2631, though the details are difficult to ascertain from their description. Ozkaya et al. [1997] compared vibration levels in new and old design subway cars and found reduced levels in the newer cars, though one of the two new cars still exceeded the FDP, and the other the comfort level.

The balance of the evidence indicates that caterpillars, excavators, bulldozers, graders, off-road forestry vehicles, heavy equipment used in mining, tractors, combines, forklifts, carrier trucks, dump
trucks, other trucks, buses, vans, trains, subway cars, helicopters, snowmobiles, cranes, and even some cars, typically expose their operators to vibration levels in excess of those recommended by ISO 2631.

3.3.4 Other Factors Influencing Vehicle Vibration Levels

A number of studies examined factors which modify the vibration exposure, including terrain, vehicle characteristics, and driving characteristics. Continuous, well-maintained, road surfaces were associated with lower vibration exposure levels [Ozkaya et al., 1994; Piette and Malchaire, 1992]. Changing grades or side slopes influenced exposure [Village et al., 1989]. Village et al. [1989] found that smaller and lighter vehicles could produce the highest vibration levels, perhaps because smaller tires are more sensitive to irregularities in the driving surface. Piette and Malchaire [1992] found that both the span of a crane, and the position of its cab influenced vibration levels, which increased with span length and when cabs were placed in the centre of the span. Suspension, of either the vehicle or the seat, does not necessarily result in a reduction in exposure. For maximum damping, the seat’s resonant frequency needs to be smaller than the frequencies produced by the vehicle. This is often not achieved, and the result is that some suspension systems can result in an amplification, rather than attenuation of the vibration exposure [Attonen and Niskanen, 1994; Burdorf and Swuste, 1996; Heino et al., 1978; Piette and Malchaire, 1992]. Ozkaya et al. [1994] demonstrated a positive association between train speed and vibration levels. Howat [1978] described increased vibration exposure with increased work rate in front-end loader operations at logging sites. Piette and Malchaire [1992] showed that on cranes with speed regulators, vibration exposure was reduced. Johanning et al. [1991] and Ozkaya et al. [1994] describe driving style and experience as factors also influencing exposure.

4. Conclusions

Epidemiological studies of the association between back disorders and vehicle operation jobs with vibration exposure show overwhelming evidence of a relationship that is consistent and strong, increases with increasing exposure, temporally precedes exposures, and is biologically plausible. The risk is elevated in a broad range of driving occupations, including truck drivers, earth moving machine operators, power shovel operators, bulldozer operators, forklift drivers, crane operators, straddle carrier operators, agricultural workers, tractor drivers, bus drivers, helicopter pilots, subway operators, reindeer herders, and vehicle drivers not otherwise specified. Exposure measurement data indicates that the vehicles used in these jobs are likely to expose workers to vibration levels in excess of ISO standards, and that common control measures, such as seat suspension, are often ineffective.

Driving occupations frequently involve sustained postures and/or lifting activities which are also associated with back disorders, therefore one might speculate that these exposures, and not vibration exposures, might be the causal factors. There are a number of arguments to support vibration as an independent risk factor for back disorders. Experimental studies suggest that sitting and rotated postures serve to increase vibration transmission, suggesting that the two factors may interact. A number of the epidemiological studies used other sedentary occupations as controls, and found elevated risks among the drivers, supporting the experimental hypothesis. Similarly, driving jobs with little lifting involved, e.g., subway train engineers, bus drivers, and crane operators, showed
elevated risks. Finally, studies using internals controls showed increasing risks with increasing vibration dose.

The data support a causal link between back disorders and both driving occupations and whole body vibration. Numerous back disorders are involved, including lumbago, sciatica, generalized back pain, and intervertebral disc herniation and degeneration. Elevated risks are consistently observed after five years of exposure.
5. References


Burdorf A, Naaktgeboren B et al. (1993) Occupational risk factors for low back pain among


Chernyuk VI. (1992). Effect of whole body vibration on diseases of the lumbar section of the spine in agricultural machinery operators. Gigaenda Truda 28:75-77


Table 1: Epidemiological Studies of Back Pain and Injuries in Vehicle Operators

<table>
<thead>
<tr>
<th>Study Characteristics</th>
<th>Exposure Measurements</th>
<th>Outcome Measurements - Relative Risk (95% CI), except where otherwise noted</th>
<th>Conclusions</th>
<th>Heirarchy of Study Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author</strong> (year)</td>
<td><strong>Study Design</strong></td>
<td><strong>Subject Group</strong></td>
<td><strong>Control Group</strong></td>
<td><strong>Confounders Controlled For</strong></td>
</tr>
<tr>
<td>Lafferty, P. and R. Hardy (1971)</td>
<td>(A)</td>
<td>128 Males and 89 Female Hospitalized Cases (aged 20 to 64)</td>
<td>Male Home Vehicle Drivers (sit in car &gt; 50% of the time)</td>
<td>Male Truck Drivers Car Drivers, Both Sexes</td>
</tr>
<tr>
<td>Frymoyer, J., et al. (1980).</td>
<td>(C)</td>
<td>2,068 Males, 3,832 Males</td>
<td>Male Motor Vehicle Drivers (sit in car &gt; 50% of the time)</td>
<td>Sedentary and Driving</td>
</tr>
<tr>
<td>Froim, P., et al. (1984).</td>
<td>(C)</td>
<td>500 Cadets</td>
<td>Male Motor Vehicle Drivers (sit in car &gt; 50% of the time)</td>
<td>Sedentary and Driving</td>
</tr>
<tr>
<td>Petrovic, L. and Milosevic, M. (1985)</td>
<td>(C)</td>
<td>44 Truck Drivers</td>
<td>Male Motor Vehicle Drivers (sit in car &gt; 50% of the time)</td>
<td>Sedentary and Driving</td>
</tr>
<tr>
<td>Brendstrup, T., and F. Biering-Sorensen (1987)</td>
<td>(A)</td>
<td>240 Male Forklift Drivers</td>
<td>Male Forklift Drivers, 66 Unskilled Workers, 31 Bricklayers</td>
<td>Forklift Drivers Working Men Unskilled Labours</td>
</tr>
<tr>
<td>Dupuis, H. and C. Zarifi (1987)</td>
<td>(C)</td>
<td>352 Operators of Earth Moving Machines Exposed to vibration ≥ 3 years</td>
<td>Self-reported prevalence of disorders of the spine = 70%, vs 54% in controls, (p=0.01)</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 - 1
<table>
<thead>
<tr>
<th>Study Characteristics</th>
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<tr>
<td>Heirarachy of Study Quality</td>
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<tr>
<td><strong>(A)</strong></td>
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</tr>
<tr>
<td>Heliövaara, M. (1987)</td>
<td>Case-Control</td>
<td>592 Men and Women with back problems, matched for age, sex, and residence</td>
<td>2,140 Men and Women without back problems, matched for age, sex, and residence</td>
</tr>
<tr>
<td><strong>(B)</strong></td>
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<tr>
<td>Bongers, P.M., et al. (1988a)</td>
<td>Cohort Study</td>
<td>743 Male Crane Operators in Steel Company</td>
<td>602 Male Floor Workers in Steel Company, with similar social class</td>
</tr>
<tr>
<td>Bongers, P.M., et al. (1988b)</td>
<td>Retrospective Cohort Study</td>
<td>743 Male Crane Operators in Steel Company</td>
<td>602 Male Floor Workers in Steel Company, with similar social class</td>
</tr>
</tbody>
</table>

**Study Characteristics**
- **Author and Year**: The author's name and the year of publication for each study.
- **Study Design**: The design of the study, such as case-control or cohort.
- **Subject Group**: The group being studied, including details like age, sex, and occupation.
- **Control Group**: The group being compared, with similar details.
- **Confounders Controlled For**: Factors that might affect the results but are controlled for in the study.
- **Job Description**: The specific job type within the study.
- **Vibration Exposure**: Details on vibration exposure within the study.
- **Back Pain or Back Trouble**: Prevalence of back pain or back trouble.
- **Sciatica**: Prevalence of sciatica.
- **Lumbar Intervertebral**: Prevalence of lumbar intervertebral disorders.
- **Other Outcomes**: Prevalence of other outcomes.
- **Comments**: Notes on the study, such as methodological considerations or limitations.

**Outcome Measurements - Relative Risk (95% CI)**
- **Relative Risk**: The relative risk of developing a condition, such as hospitalization or sciatica.
- **95% CI**: The 95% confidence interval for the relative risk.

**Conclusions**
- Descriptive comments on the findings of the study, including statistical significance and implications.

**Hierarchy of Study Quality**
- **(A)**: Good study, well done, potential for loss to follow up.
- **(B)**: Bad study, exposure to vibration not defined, subject and control group.
- **(C)**: Okay study, exposure to vibration only.

Table 1 - 2
<table>
<thead>
<tr>
<th>Study Characteristics</th>
<th>Exposure Measurements</th>
<th>Outcome Measurements - Relative Risk (95% CI), except where otherwise noted</th>
<th>Conclusions</th>
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<td><strong>Author</strong> (year)</td>
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<td><strong>Control Group</strong></td>
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<tr>
<td><strong>Heirarachy of Study Quality</strong></td>
<td><strong>Back Pain or Back Trouble</strong></td>
<td></td>
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<tr>
<td></td>
<td>2,045 Male Bus Drivers</td>
<td>1,036 Copernicus Motorists, Prevalence study.</td>
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<tr>
<td><strong>Bongers, P. M. et al. (1996). (A)</strong></td>
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<tr>
<td></td>
<td>133 Helicopter Pilots</td>
<td>228 Non-Flying Pilots</td>
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### Study Characteristics

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<th>Author</th>
<th>Study Design</th>
<th>Subject Group</th>
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<th>Exposure</th>
<th>Outcome</th>
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</tr>
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<tbody>
<tr>
<td>Boshuizen, H.C. et al. (2000a)</td>
<td>Cohort Study</td>
<td>Agriculture Workers</td>
<td>Reference Group (storage, catering, technical, maintenance)</td>
<td>&lt; 0.5 years x m²/s²</td>
<td>1 (reference)</td>
<td>Sciatica</td>
<td>This study provides some evidence of an association between driving agricultural tractors and other vibrating vehicles and long-term sickness due to back disorders, especially disc disorders. Tractor drivers show a tendency to be disabled at a younger age than the control group. Intervertebral disc disorders seem to increase with vibration dose. Vibration together with twisted posture and prolonged sitting is considered responsible for the increased incidence of back pain observed in tractor drivers. Siting is not included in the analysis as sitting and driving were too closely combined.</td>
</tr>
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<td>Boshuizen, H.C. et al. (1990a)</td>
<td>Cohort Study</td>
<td>Agriculture Workers</td>
<td>Reference Group (storage, catering, technical, maintenance)</td>
<td>0.4 m/s²</td>
<td>1 (reference)</td>
<td>Sciatica</td>
<td>The effect of tractor driving on sciatica and lumbar disc abnormalities was studied in a prospective cohort study of Dutch farmers. The prevalence of sciatica and lumbar disc abnormalities was found to be higher in tractor drivers than in the reference group. The risk did not increase with vibration intensity, possibly due to inaccuracies in measurement.</td>
</tr>
<tr>
<td>Boshuizen, H.C. et al. (1990b)</td>
<td>Cohort Study</td>
<td>Agriculture Workers who returned questionnaires in 1986</td>
<td>Reference Group (analysis by type of work)</td>
<td>0.5 years</td>
<td>24.4 (0.84-7.1)*</td>
<td>Sciatica</td>
<td>There was an association between duration and dose of exposure to vibration and back pain. The increase in the prevalence of back pain with the number of driving years and accumulated vibration dose suggests that back pain is caused by tractor driving. Twisting of the spine and static posture may also contribute to back pain in this group. The risk did not increase with vibration intensity, possibly due to inaccuracies in measurement.</td>
</tr>
</tbody>
</table>

### Exposure Measurements

<table>
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<th>Subject Group</th>
<th>Control Group</th>
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<th>Exposure</th>
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<td>24.4 (0.84-7.1)*</td>
<td>Sciatica</td>
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</table>

### Outcome Measurements - Relative Risk (95% CI), except where otherwise noted

<table>
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<th>Study</th>
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<th>Control Group</th>
<th>Confounders</th>
<th>Exposure</th>
<th>Outcome</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burdorf, A., Cross and H. Zonderland (1990)</td>
<td>53 Crane Operators in Steel Factory</td>
<td>Sedentary</td>
<td>Age, Height, Weight</td>
<td>3.6 (1.3-10.6)*</td>
<td>1-Year Prevalence</td>
<td>61% vs. 27% in controls</td>
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<tr>
<td>Videman, T., et al. (1991)</td>
<td>36 Male Calendars &lt; 64 years, employed before death, history of illness short</td>
<td>Sedentary</td>
<td>Age, Physical Loading</td>
<td>0.14 (0.03-0.7)*</td>
<td>1-Year Prevalence</td>
<td>25% vs. 10% in controls</td>
</tr>
<tr>
<td>Burdorf, A., Cross et al. (1991)</td>
<td>114 Male Concrete Manufacturing Workers</td>
<td>Sedentary</td>
<td>Age, Height</td>
<td>2.5 (1.3-4.8)*</td>
<td>1-Year Prevalence</td>
<td>25% vs. 10% in controls</td>
</tr>
</tbody>
</table>

### Cross Sectional Studies

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<th>Study</th>
<th>Subject Group</th>
<th>Control Group</th>
<th>Confounders</th>
<th>Exposure</th>
<th>Outcome</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burdorf, A., Cross et al. (1991)</td>
<td>52 Male Concrete Workers in an Engineering Factory</td>
<td>Sedentary</td>
<td>Age, Height, Weight</td>
<td>2.5 (1.3-4.8)*</td>
<td>1-Year Prevalence</td>
<td>25% vs. 10% in controls</td>
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### Table 1 - 4

<table>
<thead>
<tr>
<th>Study</th>
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<th>Confounders</th>
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<td>2.5 (1.3-4.8)*</td>
<td>1-Year Prevalence</td>
<td>25% vs. 10% in controls</td>
</tr>
<tr>
<td>Study Characteristics</td>
<td>Exposure Measurements</td>
<td>Outcome Measurements - Relative Risk (95% CI), except where otherwise noted</td>
<td>Conclusions</td>
<td>Hierarchy of Study Quality</td>
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<td><strong>Author</strong></td>
<td><strong>Study Design</strong></td>
<td><strong>Study Group</strong></td>
<td><strong>Control Group</strong></td>
<td><strong>Job Description</strong></td>
<td><strong>Vibration Exposure</strong></td>
<td><strong>Back Pain or Back Trouble</strong></td>
</tr>
<tr>
<td>Bellonera, M., et al. (C)</td>
<td>Cross Sectional</td>
<td>Professional Driving</td>
<td></td>
<td>Sex, Age, Smoking, Alcohol, Mental Stress, Previous Back Injury, Health, Body Mass Index, Parity, Occupational History, Occupational Stress (physical and mental)</td>
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<td>1.4 (1.0-2.0)*</td>
<td>1.1 (0.5-1.8)*</td>
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<tr>
<td><strong>Study Characteristics</strong></td>
<td><strong>Outcome Measurements</strong></td>
<td><strong>Prevalence of Chronic Lumbar Back Pain (%, 95% CI)</strong></td>
<td><strong>Prevalence of Total Back Pain (%, 95% CI)</strong></td>
<td><strong>Prevalence of Chronic Low Back Pain (%, 95% CI)</strong></td>
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<tr>
<td><strong>Author</strong></td>
<td><strong>Study Design</strong></td>
<td><strong>Study Group</strong></td>
<td><strong>Control Group</strong></td>
<td><strong>Job Description</strong></td>
<td><strong>Vibration Exposure</strong></td>
<td><strong>Prevalence of Chronic Lumbar Back Pain</strong></td>
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<td>Sex, Age, Smoking, Alcohol, Mental Stress, Previous Back Injury, Health, Body Mass Index, Parity, Occupational History, Occupational Stress (physical and mental)</td>
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<td><strong>Study Characteristics</strong></td>
<td><strong>Exposure Measurements</strong></td>
<td><strong>Relative Risk (95% CI)</strong></td>
<td><strong>Relative Risk (95% CI)</strong></td>
<td><strong>Relative Risk (95% CI)</strong></td>
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<td><strong>Study Design</strong></td>
<td><strong>Study Group</strong></td>
<td><strong>Control Group</strong></td>
<td><strong>Job Description</strong></td>
<td><strong>Vibration Exposure</strong></td>
<td><strong>Back Pain or Back Trouble</strong></td>
</tr>
<tr>
<td>Bellonera, M., et al. (C)</td>
<td>Cross Sectional</td>
<td>Professional Driving</td>
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<td>Sex, Age, Smoking, Alcohol, Mental Stress, Previous Back Injury, Health, Body Mass Index, Parity, Occupational History, Occupational Stress (physical and mental)</td>
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</tbody>
</table>

- **Objective**: Investigate the relationship between vibration exposure and back pain or back trouble among commercial travelers and drivers.
- **Methods**:
  - **Participants**: 1,279 commercial travelers (1,376 male, 343 female) and 200 male drivers of dumpers, tractors, earthmovers, or construction workers of similar age distribution.
  - **Exposure**: Vibration exposure assessed by years of employment and vibration intensity.
  - **Outcome**: Prevalence of low back pain.

- **Main Findings**:
  - Vibration exposure was significantly associated with low back pain.
  - The prevalence of low back pain was highest in crane operators and straddle carrier drivers.

- **Conclusions**:
  - Vibration exposure is a problem for occupational health. The subjects in this study may have been too young to show symptoms of the effects of a driving career yet. Statistical analysis was very limited and not all methods were described.


- **Objective**: Investigate the relationship between vibration exposure and low back pain among commercial travelers.
- **Methods**:
  - **Participants**: 1,719 commercial travelers.
  - **Exposure**: Vibration exposure assessed by years of employment and vibration intensity.
  - **Outcome**: Prevalence of low back pain.

- **Main Findings**:
  - A regression analysis found a positive relationship between lumbago prevalence and the total service related dose of vibration.
  - Cold and stress were considered other possible contributors to the drivers’ back problems.

- **Conclusions**:
  - Vibration exposure: A regression analysis found a positive relationship between lumbago prevalence and the total service related dose of vibration. Cold and stress were considered other possible contributors to the drivers’ back problems.

**Table 1 - 6**

Study Characteristics

<table>
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<tr>
<th>Author</th>
<th>Study Design</th>
<th>Subject Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mayushira, K., et al. (1992)</td>
<td>Cross sectional</td>
<td>Commercial Travelers (aged 30 - 49)</td>
</tr>
<tr>
<td>Pietri, F., et al. (1993)</td>
<td>Cross sectional</td>
<td>Commercial Travelers, hours driving per week: 10 to 14</td>
</tr>
<tr>
<td>Bottom, A., et al. (1993)</td>
<td>Cross sectional</td>
<td>Commercial Travelers, hours driving per week: 11 to 20</td>
</tr>
<tr>
<td>Rappo, R. and M. Moniz (1993)</td>
<td>Cross sectional</td>
<td>Commercial Travelers, hours driving per week: 21 to 30</td>
</tr>
<tr>
<td>Bevresten, M. Cross and A. Betta (1994)</td>
<td>Cross sectional</td>
<td>Commercial Travelers, hours driving per week: ≥ 25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Control Group</th>
<th>Confounders Controlled For</th>
<th>Vibration Exposure</th>
<th>Outcome Measurements - Relative Risk (95%), CI, except where otherwise noted</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Back Pain or Back Trouble</td>
<td>Sciatic</td>
</tr>
<tr>
<td>Mayushira, K., et al. (1992)</td>
<td>Cross sectional</td>
<td>Commercial Travelers (aged 30 - 49)</td>
<td>Prevalence: 38% (NS)</td>
<td>60%</td>
</tr>
<tr>
<td>Pietri, F., et al. (1993)</td>
<td>Cross sectional</td>
<td>Commercial Travelers, hours driving per week: 10 to 14</td>
<td>Prevalence: 60%</td>
<td>40%</td>
</tr>
<tr>
<td>Bottom, A., et al. (1993)</td>
<td>Cross sectional</td>
<td>Commercial Travelers, hours driving per week: 11 to 20</td>
<td>Prevalence: 40% vs. 20% in Controls</td>
<td>60%</td>
</tr>
<tr>
<td>Rappo, R. and M. Moniz (1993)</td>
<td>Cross sectional</td>
<td>Commercial Travelers, hours driving per week: 21 to 30</td>
<td>Prevalence: 31% vs. 20% in Controls</td>
<td>60%</td>
</tr>
<tr>
<td>Bevresten, M. Cross and A. Betta (1994)</td>
<td>Cross sectional</td>
<td>Commercial Travelers, hours driving per week: ≥ 25</td>
<td>Prevalence: 40% vs. 20% in Controls</td>
<td>60%</td>
</tr>
</tbody>
</table>

**Hierarchy of Study Quality**

- **Mayushira, K., et al. (1992)**: Cross sectional Study of Vibration Exposure and Back Pain or Back Trouble in Commercial Travelers (aged 30 - 49) and Commercial Drivers of Dumpers, Tractors, Earthmovers, in Construction and Agriculture.
- **Pietri, F., et al. (1993)**: Cross sectional Study of Vibration Exposure and Back Pain or Back Trouble in Commercial Travelers.
- **Bevresten, M. Cross and A. Betta (1994)**: Cross sectional Study of Vibration Exposure and Back Pain or Back Trouble in Commercial Travelers.

**Table 1 - 6**

**Table Notes**

- **Shovel Operators**: 127 Bulldozer Operators, 44 Forklift Operators (aged 30 - 49)
- **Sociodemographics**: Age, Height, Weight, Occupational History, Psychological Stress, Climatic Conditions, Job Satisfaction.
- **Health effects data done strangely, No exposure data, but this a recent German article (translated)**
- **Good study, although the methods for the incidence study are not clear (I.e. not a great study, confounders?)**
- **Study will done, but I thought they dismissed it, n = 3, r = 1**
- **Health effects data done strangely. No exposure data, but this is a recent German article (translated)**

**Table 1 - 6**

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<table>
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<tr>
<th>Study Characteristics</th>
<th>Exposure Measurements</th>
<th>Outcome Measurements - Relative Risk (95% CI), except where otherwise noted</th>
<th>Conclusions</th>
<th>Hierarchy of Study Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author (year)</td>
<td>Study Design</td>
<td>Subject Group</td>
<td>Control Group</td>
<td>Confounders Controlled For</td>
</tr>
<tr>
<td>Heirarachy of Study Quality</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barbiers, G., et al. (1995)</td>
<td>Cross Sectional Study</td>
<td>29 Male Tractor Drivers with &gt; 5 years of employment</td>
<td>100 Unexposed Males, with similar weight, height, and age</td>
<td>Age (Stratified)</td>
</tr>
<tr>
<td>Masset, D. and J. Melchare (1994)</td>
<td>Cross Sectional Study</td>
<td>658 Blue Collar Stud Workers (aged &gt; 40)</td>
<td>Internal Reference Group (analysis by duration of driving)</td>
<td>Age, Sensitivity, Height, Weight, General Health, Chronic Disease, Accidents, Personality, Smoking, Sports, Satisfactions with Family and Occupation, Abnormal Fatigue, Depressive Tendency, Irritated Temper, Headache.</td>
</tr>
<tr>
<td>Guo, H-R., et al. (1995)</td>
<td>Cohort Study</td>
<td>5,256 workers</td>
<td>24,818 other workers from the US National Health Interview Survey</td>
<td>Sex (stratified) and Weighting to Structure of US Population (incompletely described)</td>
</tr>
<tr>
<td>Jensen, M.F. Cohort Study (1993)</td>
<td>Study</td>
<td>89,146 Male Professional Drivers (aged 15-59)</td>
<td>3.1 million Employed Swedish Males (aged 15-59)</td>
<td>Age, Calendar Year</td>
</tr>
</tbody>
</table>

Table 1 - 7
<table>
<thead>
<tr>
<th>Study Characteristics</th>
<th>Exposure Measurements</th>
<th>Outcome Measurements - Relative Risk (95%, CI), except where otherwise noted</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author (year)</strong></td>
<td><strong>Study Design</strong></td>
<td><strong>Subject Group</strong></td>
<td><strong>Control Group</strong></td>
</tr>
<tr>
<td>Heirarachy of Study Quality</td>
<td></td>
<td><strong>Back Pain or Back Trouble</strong></td>
<td><strong>Sciatica</strong></td>
</tr>
<tr>
<td>Liz, J., et al. (1996)</td>
<td>Cross Sectional</td>
<td>68,920 Ontario Residents (aged 16-64)</td>
<td>Internal Reference Group (analyzed by occupational risk factors)</td>
</tr>
<tr>
<td>Magnusson, M.L., et al. (1996).</td>
<td>Cross Sectional</td>
<td>111 Male Bus Drivers, 117 Male Truck Drivers</td>
<td>17 Male Sedentary &amp; Wk</td>
</tr>
<tr>
<td>Xu, Y., et al. (1997)</td>
<td>Cross Sectional</td>
<td>5,185 randomly sampled members of the Danish population who were employed in 1990 (aged 18 - 59)</td>
<td>Internal reference group (analyzed by risk factors)</td>
</tr>
<tr>
<td>Thorbjörnsson, C.O.B., et al. (1998)</td>
<td>Cross Sectional; Cohort</td>
<td>252 Women, 232 Men (aged 42-58)</td>
<td>Internal reference group (analyzed by risk factors)</td>
</tr>
</tbody>
</table>

Table 1 - 8

A = well-designed studies  
B = good studies, with a few deficiencies  
C = studies with a number of deficiencies, useful mainly as contributors to overall evidence  
CI = Confidence Interval  
* = multivariate analysis, adjusting for all confounders  
† = multivariate analysis, adjusting for selected confounders  
NS = not statistically significant, probability that result is due to chance is greater than 5%  
p = statistically significant, with only a small probability that result is due to chance
## Table 2: Levels of Exposure to Whole Body Vibration in Vehicle Operators

<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Industry; Study Conditions; Study Objectives</th>
<th>Vehicle Types</th>
<th>Vehicle Specifics</th>
<th>Vibration Exposure Levels (Exposure in Root Mean Square m/s² unless otherwise specified)</th>
<th>Dominant Vibration Frequencies (Hz)</th>
<th>Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)</th>
<th>Peak Exposure or Crest Factors (CF, $h_{\text{peak}}/h_{\text{rms}}$)</th>
<th>Jobs and shocks</th>
<th>Determinants of Vibration Exposure (other than vehicle type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Heino, Ketola, Makela, Mäkinen, Niemelä, Starck, and Partanen, 1978]</td>
<td>Locomotive engineers; Mostly with loco/s running on main tracks; Exposure assessment.</td>
<td>Vehicle Types</td>
<td>Vehicle Specifics</td>
<td>NR</td>
<td>In general, highest components of z-axis vibration were at 2 – 4 Hz.</td>
<td>72 % of measurements &gt; EL</td>
<td>NR</td>
<td>NR</td>
<td>Vibration dampers in seat only effective &gt; 10 Hz (5-10dB damping). Vibration at 2.5 Hz may be up to 5dB higher at seat than floor. Inflexible bogies on mid-cab design.</td>
</tr>
<tr>
<td>[Howat, 1978]</td>
<td>Forestry Vehicles; Dry-land sort; Exposure assessment.</td>
<td>Forestry equipment operators; Road and off road Conditions; comparing subjective evaluation with objective measurements.</td>
<td>At seat; Tri-axial accelerometers; Samples &lt; 4 minutes.</td>
<td>Caterpillar 966 (Manuf. 1973); Caterpillar 966 (Manuf. 1977); Caterpillar 980; Caterpillar 988</td>
<td>Exceeds 1 m/s² ~95% of observations; Exceeds 1 m/s² ~65% of observations; Exceeds 1 m/s² ~55% of observations; Exceeds 1 m/s² ~15% of observations.</td>
<td>NR</td>
<td>99% obs &gt; 8-hour ISO FDP</td>
<td>NR</td>
<td>Work rate</td>
</tr>
<tr>
<td>[Hansson and Wikstrom, 1981]</td>
<td>Forestry equipment operators; Road and off road Conditions; comparing subjective evaluation with objective measurements.</td>
<td>At seat; Tri-axial accelerometers; 15 minute sample.</td>
<td>Off-road forestry vehicles; 42 drivers.</td>
<td>$h_{\text{rms},z}=0.18 – 1.78$ m/s²</td>
<td>$z$-axis $=1.5 – 3.0$ Hz.</td>
<td>NR</td>
<td>92% obs &gt; 8-hour ISO FDP</td>
<td>NR</td>
<td>Speed, surface smoothness and terrain</td>
</tr>
<tr>
<td>[Redmond and Remington, 1986]</td>
<td>Coal Mining; Normal operating conditions; Exposure assessment study.</td>
<td>Coal mining vehicles</td>
<td>Surface and underground vehicles (N=86 samples).</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>SR</td>
</tr>
</tbody>
</table>

### Determinants of Vibration Exposure (other than vehicle type)

- Vibration dampers in seat only effective > 10 Hz (5-10dB damping).
- Vibration at 2.5 Hz may be up to 5dB higher at seat than floor.
- Inflexible bogies on mid-cab design.
- Work rate.
<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Industry; Study Conditions; Study Objectives</th>
<th>Measurement Location; Device Type; Sample Duration</th>
<th>Vehicle Types</th>
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<th>Vibration Exposure Levels (Exposure in Root Mean Square m/s² unless otherwise specified)</th>
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<th>Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)</th>
<th>Peak Exposure or Crest Factors (CF, $\text{CF}<em>{\text{peak}}/\text{CF}</em>{\text{rms}}$)</th>
<th>Jobs and shocks</th>
<th>Determinants of Vibration Exposure (other than vehicle type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redmond and Remington, Cont’d</td>
<td>Personnel carrier Haulage vehicle Bridge conveyor</td>
<td>Crane operators; Operating conditions NR; Health Study</td>
<td>Crane Operators</td>
<td>$a_{\text{vz}} = 0.25 - 0.67 \text{ m/s}^2$</td>
<td>NR</td>
<td>6.0</td>
<td>6.0</td>
<td>SR</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>[Bongers, Boshuizen, Boshuizen, Hulshof and Koemeester, 1988a]</td>
<td>&quot;In agreement with ISO 2631 guidelines&quot;.</td>
<td></td>
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<tr>
<td>[Netterstrom and Juel, 1989]</td>
<td>NR</td>
<td>Bus drivers; Operating conditions NR; Health Study</td>
<td>Bus Drivers.</td>
<td>Bus Drivers.</td>
<td>105 dB Acceleration given for 3 - 20 Hz range.</td>
<td>NR</td>
<td></td>
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</tr>
<tr>
<td>[Village, Morrison and Leong, 1989]</td>
<td>NR</td>
<td>Mining; Normal operating conditions; Exposure assessment.</td>
<td>At seat; Tri-axial accelerometers; Sampled over set of standard tasks.</td>
<td>Load-haul-dump vehicles (N=22 samples).</td>
<td>$a_x = 0.5 - 1.0; a_y = 0.6 - 0.7; a_z = 0.7 - 1.4$ $a_x = 0.4 - 1.4; a_y = 0.5 - 0.6; a_z = 0.6 - 1.6$ $a_x = 0.6 - 0.8; a_y = 0.6 - 0.8; a_z = 0.8 - 1.2$ $a_x = 0.5 - 1.5; a_y = 0.6 - 0.7; a_z = 0.8 - 2.5$ $x,y: 1.6 - 2.0$ $z = 3.15$ Hz</td>
<td>20/22 sets of measurements exceed ISO 2631; 90% of vehicles exceeded EL$_x$ and EL$_z$, 52% exceeded EL$_y$.</td>
<td>Using ISO task-based scheme, all samples &gt; EL</td>
<td>76% (mine A), 43% of samples (mine B) exceeded crest factor of 6.</td>
<td>Drivers exposed to random jolts of &gt; 20 m/s², well in excess of ISO 2631. Operators leave seat, creating additional impact forces.</td>
<td>Significant differences between vehicle sizes and tasks, also vehicle/task interaction; Other potential determinants: road conditions, tire type, size and pressure, seating suspension.</td>
</tr>
<tr>
<td>[Boshuizen, Boshuizen, Hulshof and Bongers, 1990]</td>
<td>Agricultural vehicles; Normal working conditions; Health Study.</td>
<td>Measurement location NR; Triaxial accelerometer; Sample duration NR.</td>
<td>Tractors, bulldozers, combine harvesters, lorry, van and car.</td>
<td>Tractor in field (n=4) Heavy tractor in field Tractor on asphalt road (n=4) Tractor and trailer on asphalt Tractor on brick road (n=3) Bulldozer, standard seat (n=3) Bulldozer, anti-vibrat'n seat (n=4) Combine harvester Lorry Van Car</td>
<td>$a_{\text{vector sum}} = 0.50 - 0.59$ $a_{\text{vector sum}} = 1.47$ $a_{\text{vector sum}} = 0.67 - 0.98$ $a_{\text{vector sum}} = 1.17$ $a_{\text{vector sum}} = 1.76 - 2.03$ $a_{\text{vector sum}} = 0.52 - 0.64$ $a_{\text{vector sum}} = 0.43 - 0.80$ $a_{\text{vector sum}} = 0.28$ $a_{\text{vector sum}} = 0.78$ $a_{\text{vector sum}} = 0.37$ $a_{\text{vector sum}} = 0.25$</td>
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<tr>
<td>Author/year</td>
<td>Industry; Study Conditions; Study Objectives</td>
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<td><strong>Table 2 - 3</strong></td>
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<tr>
<td>[Bongers, Hulshof, et al, 1990]</td>
<td>Helicopter pilots; Representative flight conditions; Health study.</td>
<td>Measurement location NR; Triaxial accelerometer; Sample duration NR.</td>
<td>4 Helicopter types, two vehicles of each type measured.</td>
<td>Alouette III</td>
<td>(a_{x}=0.12-0.17, \ a_{y}=0.17-0.25, \ a_{z}=0.44-0.67)</td>
<td>x, y, z = 16</td>
<td>FDP reached at 2-4 hrs at (a_{x})</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
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<td></td>
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<td>Bolkow 105</td>
<td>(a_{x}=0.09-0.13, \ a_{y}=0.13-0.18, \ a_{z}=0.29-0.49)</td>
<td>x, z = 25, y = 6</td>
<td>FDP reached at 3-7 hrs at (a_{x})</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
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<td></td>
<td>Sikorsky 61</td>
<td>(a_{x}=0.06-0.11, \ a_{y}=0.10-0.21, \ a_{z}=0.17-0.44)</td>
<td>x, y = 16, z=8</td>
<td>FDP reached at 4-13 hrs at (a_{x})</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
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<td></td>
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<td></td>
<td>Sikorsky 76</td>
<td>(a_{x}=0.24-0.55, \ a_{y}=0.07-0.14, \ a_{z}=0.10-0.19, \ a_{z}=0.17-0.36)</td>
<td>x, y = 20, z=8</td>
<td>FDP reached at 5-10 hrs at (a_{z})</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>[Griffen, 1990]</td>
<td>Road and agricultural vehicles; Normal operating conditions; Exposure assessment.</td>
<td>Seat; Triaxial accelerometer; 15-30 minute samples.</td>
<td>Various road and agricultural vehicles.</td>
<td>Autos, and Vans (n=11)</td>
<td>(a_{x}=0.25 – 1.00)</td>
<td>NR</td>
<td>Exceed FDP</td>
<td>Exceed EL</td>
<td>Road surface</td>
<td></td>
</tr>
<tr>
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<td></td>
<td>Trucks (n=3)</td>
<td>(a_{x}=0.40 – 1.75)</td>
<td>NR</td>
<td>-</td>
<td>-</td>
<td>NR</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td>Buses (n=3)</td>
<td>(a_{x}=0.60 – 1.30)</td>
<td>NR</td>
<td>-</td>
<td>-</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Auto (city road)</td>
<td>(a_{x}=0.43)</td>
<td>5 hours</td>
<td>-</td>
<td>-</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Van Country road</td>
<td>(a_{x}=0.89)</td>
<td>2 hours</td>
<td>5 hours</td>
<td>4.8</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Truck Rough road</td>
<td>(a_{x}=1.06)</td>
<td>1.5 hours</td>
<td>4 hours</td>
<td>3.9</td>
<td>NR</td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Tractors, mowing</td>
<td>(a_{x}=1.20)</td>
<td>1 hour</td>
<td>-</td>
<td>6.3</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tractors, hay turning</td>
<td>(a_{x}=2.00)</td>
<td>40 minutes</td>
<td>-</td>
<td>8.5</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tractors, farm road</td>
<td>(a_{x}=2.24)</td>
<td>15 minutes</td>
<td>-</td>
<td>4.2</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>[Johanning, Wilder, Landrigan, and Pope, 1991]</td>
<td>Subway trains; Normal operating conditions; Exposure assessment.</td>
<td>At seat; Tri-axial accelerometer; Approx. 2 hrs of data.</td>
<td>Old (1948) to new (1988) subway cars.</td>
<td>Mean of all car types:</td>
<td>(a_{x}=0.25) (range 0.32 – 0.99)</td>
<td>1 – 2 Hz (lateral)</td>
<td>Using vector sum averages, concluded operators should not be exposed more than an average of 3.75 hours/day (based on FDP).</td>
<td>NR</td>
<td>NR</td>
<td>Suggest inter-car differences based on: Track conditions, train speed, vehicle maintenance, driving style.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Specific car types:</td>
<td>(a_{x}=0.10), (a_{y}=0.26)</td>
<td>2.5 and 12.5 Hz (Vertical)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R10 cars (manuf. 1948)</td>
<td>(a_{x}=0.37)</td>
<td>Meaning of all car types:</td>
<td>NR</td>
<td>NR</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R68 cars (manuf. 1988)</td>
<td>(a_{x}=0.10), (a_{y}=0.21), (a_{z}=0.33)</td>
<td>NR</td>
<td>NR</td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>(a_{x}=0.08), (a_{y}=0.19), (a_{z}=0.29)</td>
<td>NR</td>
<td>NR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Boshuizen, Bongers, Hulshof, 1992]</td>
<td>Heavy equipment; Normal working conditions; Health study.</td>
<td>At seat; Tri-axial accelerometer; Sample duration approx. 5 min.</td>
<td>2 forklifts and freight tractor.</td>
<td>Small forklift</td>
<td>(a_{x}=0.80 \text{m/s}^2)</td>
<td>3.15 Hz</td>
<td>Acceleration levels for forklifts exceeded FDP 4-hour limit; levels for tractor exceeded 2.5 hour limit.</td>
<td>NR</td>
<td>NR</td>
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<td></td>
<td>Large forklift</td>
<td>(a_{x}=0.79 \text{m/s}^2)</td>
<td>2.5 Hz</td>
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<td></td>
<td></td>
<td>Freight container tractor</td>
<td>(a_{x}=1.04 \text{m/s}^2)</td>
<td>1.6, 2.5 Hz</td>
<td></td>
<td></td>
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<tr>
<td>Author (year)</td>
<td>Industry; Study Conditions; Study Objectives</td>
<td>Measurement Location; Device Type; Sample Duration</td>
<td>Vehicle Types</td>
<td>Vehicle Specifics</td>
<td>Vibration Exposure Levels <em>(Exposure in Root Mean Square m/s² unless otherwise specified)</em></td>
<td>Dominant Vibration Frequencies (Hz)</td>
<td>Compliance with ISO 2631 <em>(EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)</em></td>
<td>Peak Exposure or Crest Factors (CF, ( a_{peak}/a_{rms} ))</td>
<td>Jobs and shocks</td>
<td>Determinants of Vibration Exposure <em>(other than vehicle type)</em></td>
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<tr>
<td>[Bovenzi and Zadini, 1992]</td>
<td>Bus Drivers; Actual driving conditions; Health study.</td>
<td>Seat; Triaxial accelerometer; 15-30 minute samples.</td>
<td>Older Fiat buses (manuf. 1968-1973), Newer Inveco and Inbus buses (manuf. 1987-1990).</td>
<td>Fiat 409 DSU</td>
<td>( a_{yz} = 0.12, a_{xz} = 0.16, a_{yx} = 0.65, a_{yztot} = 0.15 )</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>Authors comment that seat suspension in old Fiat buses (transmissibility, ( T = a_{yz, seat}/a_{yz, floor} )) varied from 1.6 to 1.9, while in newer Inbus and Inveco buses ( T = 1.1 ) to 1.25.</td>
</tr>
<tr>
<td>[Piette and Malchaire, 1992]</td>
<td>Steel works; Normal operating conditions; Determinants of exposure analysis.</td>
<td>At seat and floor; Tri-axial accelerometers; 2 minute samples.</td>
<td>70 Cranes.</td>
<td>Mid-span cab End cab</td>
<td>( a_{yz} = 0.37 – 1.16, a_{xy} = 0.26 – 1.03 )</td>
<td>Peaks found at 4 - 8 Hz</td>
<td>6/21 cranes in excess of FDP; none above EL.</td>
<td>NR</td>
<td>Shocks apparent from time-traces of Z-axis measurements (Fig 5).</td>
<td>Crane span, load, runway condition, cabin position, suspension, seat, speed.</td>
</tr>
<tr>
<td>[Burdorf, Naaktgebore, and de Groot 1993]</td>
<td>Port workers; Variety of working conditions; Health study.</td>
<td>Measurement location NR; Tri-axial accelerometers; 5 min samples.</td>
<td>20 Cranes, 21 straddle carriers.</td>
<td>Cranes Straddle carriers</td>
<td>( a_{yz} = 0.15, a_{xz} = 0.11, a_{xy} = 0.17 )</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>[Burdorf and Swuste, 1993]</td>
<td>Professional Drivers; Normal working conditions; Study of attenuation efficiency of suspension seats.</td>
<td>Seat and Floor; Tri-axial accelerometer but study limited to ( a_{yz} ); sample duration 5 min.</td>
<td>Lorries Fork lifts Tractors.</td>
<td>Lorries Fork lifts Tractors</td>
<td>( a_{yz} = 0.50 – 0.99, a_{xz} = 0.55 – 0.89, a_{xy} = 0.36 – 0.92 )</td>
<td>1.15 – 2.7 Hz</td>
<td>All worksite measurements exceeded 8hr ISO 2631 FDP level, and 9/24 worksites exceeded EL.</td>
<td>NR</td>
<td>NR</td>
<td>Seat suspension characteristics: Mean Seat transmissibility ( T = a_{yz, seat}/a_{yz, floor} ) varied from 0.34 – 1.31.</td>
</tr>
<tr>
<td>[Anttonen and Niskanen, 1994]</td>
<td>Reindeer herding; Typical working conditions; Exposure assessment.</td>
<td>At seat and foot board; Tri-axial accelerometers; Sample duration 10 – 50 minutes.</td>
<td>Snowmobiles: Old (1974) to New (1993) designs.</td>
<td>Snowmobile: Old 1983 frame 1988 seat 1994 frame Snowmobile: New 1983 frame 1988 seat 1994 frame</td>
<td>( a_{yz, seat} = 1 )</td>
<td>2.6 Hz, 4.40 Hz, 2.20 Hz, 10.63 Hz, 2 Hz, 8 Hz</td>
<td>Majority of measurements exceeded proposed European standards ( 0.7 ) m/s², ceiling value.</td>
<td>NR</td>
<td>Shocks considered high risk for snowmobilers.</td>
<td>Seat resonance (i.e. amplifying rather than attenuating frame vibration), uneven terrain, speed.</td>
</tr>
</tbody>
</table>

Table 2 - 4
<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Industry; Study Conditions; Study Objectives</th>
<th>Measurement Location; Device Type; Sample Duration</th>
<th>Vehicle Types</th>
<th>Vehicle Specifications</th>
<th>Vibration Exposure Levels (Exposure in Root Mean Square m/s² unless otherwise specified)</th>
<th>Dominant Vibration Frequencies (Hz)</th>
<th>Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)</th>
<th>Peak Exposure or Crest Factors (CF, $a_{peak}/a_{rms}$)</th>
<th>Jobs and shocks</th>
<th>Determinants of Vibration Exposure (other than vehicle type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Bovenzi and Betta, 1994]</td>
<td>Tractors; Normal operating conditions; Health study.</td>
<td>At seat; Tri-axial accelerometer; Sampling duration NR.</td>
<td>Low-power tractors (45-85 hp).</td>
<td>Fiat (50-70 hp) n = 14 Ford (45-60 hp) n=23 Fendt (58-64 hp) n=9 International (58 hp) n=2 Lamborghini (65-80 hp) n=2 Massey Ferguson (50-85 hp) n=3</td>
<td>$a_{peak}/a_{rms}$ = 1.24 (mean, range = 0.58-2.00) $a_{peak}/a_{rms}$ = 0.96 (mean, range = 0.36-2.03) $a_{peak}/a_{rms}$ = 0.89 (mean, range = 0.53-1.25) $a_{peak}/a_{rms}$ = 1.08 (mean, range = 0.85-1.30) $a_{peak}/a_{rms}$ = 1.05 (mean, range = 0.86-1.25) $a_{peak}/a_{rms}$ = 1.41 (mean, range = 0.84-1.82)</td>
<td>2.5 - 4 Hz</td>
<td>For estimated daily average exposure (2.7 hours), mean value of frequency weighted acceleration is below EL.</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
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<tr>
<td>[Ozkaya, Willems and Goldsheyder, 1994]</td>
<td>Subway trains; Normal operating conditions; Exposure assessment.</td>
<td>At seat; Tri-axial accelerometer; 48 round trips giving 100 hours of data.</td>
<td>Subway car .</td>
<td>16 different types</td>
<td>Average acceleration (by subway line) ranging from 0.37 m/s² to 0.57 m/s²</td>
<td>NR</td>
<td>Exposure levels above ISO 2631 FDP on 6/20 lines; none over EL.</td>
<td>NR</td>
<td>NR</td>
<td>Speed, track type and condition, car type, maintenance, passenger load, driver experience.</td>
</tr>
<tr>
<td>[Barbieri, Mattoli, Grillo, Gemmini, Mancini and Raffi, 1995]</td>
<td>Tractors; Operating conditions NR; Health study.</td>
<td></td>
<td>Agricultural tractors.</td>
<td>Agricultural tractors</td>
<td>50% of tractors acceleration between 1.16 m/s² and 1.93 m/s²</td>
<td>$z = 4.5$</td>
<td>FDP exceeded in between 21 and 58 minutes at 1.16 m/s² and 1.93 m/s² respectively.</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>[Suvorov, Staroezhuk, Tsentila, and Lagutina, 1996]</td>
<td>Heavy equipment; Conditions NR; Exposure assessment.</td>
<td>Measurement location NR; Device type NR; Summary data of 10,000+ obs.</td>
<td>Heavy equipment – 90 different vehicle types.</td>
<td>Tractor Bulldozers Open Mine Excavator Drill Rig</td>
<td>69 dB</td>
<td>69 dB</td>
<td>60 dB</td>
<td>58 dB</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>[Ozkaya, Goldsheyder and Willems, 1997]</td>
<td>Subway trains; Normal operating conditions; Exposure assessment.</td>
<td>At seat; Tri-axial accelerometer; Sampling duration between 43 and 660 sec.</td>
<td>2 new-technology subway trains.</td>
<td>“A-line”, new car “A-line”, old car “2-line”, new car “2-line”, old car</td>
<td>$a_{peak} = 0.18$; $a_{peak}/a_{rms} = 0.38$ $a_{peak} = 0.27 – 0.34$; $a_{peak}/a_{rms} = 0.51 – 0.53$ $a_{peak} = 0.12$; $a_{peak}/a_{rms} = 0.26$ $a_{peak} = 0.29$; $a_{peak}/a_{rms} = 0.38$</td>
<td>NR</td>
<td>Older cars both exceed FDP boundary; new car only 23% of FDP boundary.</td>
<td>NR</td>
<td>NR</td>
<td>Suspension, air better than springs.</td>
</tr>
<tr>
<td>[Robinson, Martin, Roddian, Gibb, and Duntall, 1997]</td>
<td>Mining; Typical operating conditions; Exposure assessment for return to work planning.</td>
<td>At seat; Tri-axial measurements; Sampling duration NR.</td>
<td>Representative sample of mine equipment.</td>
<td>Heavy Trucks Light Trucks Earth Movers</td>
<td>$a_{peak} = 0.7 – 1.0$ $a_{peak} = 1.0 – 2.0$ $a_{peak} = 0.7 – 1.0$</td>
<td>NR</td>
<td>All vehicles &gt; ISO 2631 FDP8hr. Range of Vibration Dose Value (VDV) x = 13 – 33 m/s¹.⁷²</td>
<td>$CF_p = 7.8 – 18.8$ $CF_p = 7.4 – 17.5$ $CF_p = 10.6 – 24.0$</td>
<td>Total of 8 of 11 vehicles CF &gt; 10</td>
<td>Vehicle and roadway maintenance.</td>
</tr>
<tr>
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<tr>
<td>Futatsuka, Maeda, Inaoka, Nagano, Shono, and Miyakita, 1998</td>
<td>Agricultural equipment; Normal working conditions; Exposure assessment.</td>
<td>At seat; Tri-axial measurements; Each vehicle tested on 4 runs, each of 30 sec duration.</td>
<td>Combine (Iseki HL3700)</td>
<td>a_rms = 0.41</td>
<td>NR</td>
<td>All vehicle above FDP 8-hour limit. Four vehicles (Yanmar combine, Kubota tractor, Yanmar carrier and the tea-picker) were above the 8-hour EL.</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
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<tr>
<td>Holmlund and Lundstrom, 1999</td>
<td>Heavy equipment; Normal working conditions; exposure assessment.</td>
<td>NR</td>
<td>Several heavy equipment types (N=57).</td>
<td>NR</td>
<td>NR</td>
<td>6.2 (3.2 - 8.4)</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
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</tr>
</tbody>
</table>

1 Not Reported
2 authors report "ISO risk limit", assume they mean "exposure limit"
3 Crest factors > 20 m/s² could not be measured accurately
4 Seat back measure
5 From Bovenzi, 1996
6 $a_{\text{rms}} = (2a_{\text{vx}} + a_{\text{vy}}^2 + a_{\text{vz}}^2)^{0.5}$
7 While the majority of seats attenuated vibration exposure (83%), some amplified exposure (T>1).
8 Assume these are vector sums: $a_{\text{rms,vx}} = (1.4 a_{\text{vx}}^2 + 1.4 a_{\text{vy}}^2 + a_{\text{vz}}^2)^{0.5}$
9 Reference values calculated as $2.5 \times 10^6$
10 VDV Vibration Dose Value (BS6841); VDV should not exceed 15 m/s^{1.75}