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

A Review of the Scientific Evidence

Report to:

Randy Lane,
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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, NIOSHTIC, Ergoweb, and Arbline) 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, OH, July 1997; and

- “Back Disorders and Whole-Body Vibration in Equipment Operators and Truck Drivers Epidemiology, Pathology, and Exposure Limits” by Murray Lott and Judy Village, 1998, and its 1999 addendum.

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 work forces 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; Throbjornsson 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/s^2 or dB) and vibration dose (in units of time multiplied by vibration acceleration squared, i.e., year x m^2/s^4). 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 lumber 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-Sorensen, 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-illiac 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/s^2 (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/s^2. Suvorov et al. [1996] appear to have used a reference level of 2.5 x 10^{-6} m/s^2.

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/s^2, 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:

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

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.

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

Study Characteristics					Exposure Measurements		Outcome Measurements - Relative Risk (95% CI), except where otherwise noted				Conclusions		
Author (year)	Study Design	Subject Group	Control Group	Confounders Controlled For	Job Description	Vibration Exposure	Back Pain or Back Trouble	Sciatica	lumbar intervertebral	Other Outcomes		Comments	Heirarachy of Study Quality
Kelsey, J., and R. Hardy. (1975). **(A)**	Case-Control	128 Males and 89 Female Hospitalized Cases (aged 20 to 64)	217 Hospital Controls, age and sex matched, similar race and social class	Age, Sex	Male Motor Vehicle Drivers (sit in car > 50% of the time)				2.75 (p<0.02)		A clear trend that occupational driving is a risk factor for herniated disc emerged across surgical, probable, and possible cases. People who spent half or more of their time driving had a 3 times greater likelihood of developing acute herniated lumbar disc than those who did not have such jobs. Neither frequency nor amount of lifting on the job was related to the development of acute herniated lumbar disc. The relative risk for sitting while driving was twice as high as the relative risk for sitting in a chair. Confounders were not significant in the analysis. Of six of the surgical cases, 5 had L4 herniations. Driving may be a strong risk factor for herniations at the L4 level.		Very often reference study
					Male Truck Drivers				4.67 (p<0.02)				
					Car Drivers, Both Sexes				2.16 (p<0.01)				
Frymoyer, J., et al. (1980). **(C)**	Cross Sectional	1,852 Males, 2,068 Females aged 18 - 55, visiting university family practice unit	Internal Reference Group (occupational risk factors)				Males (calculations from data) / Females (calculations from data)				Medically reported low back pain was associated with driving, truck driving, lifting, carrying, pulling, pushing and twisting, as well as non-driving vibration. The medical records design did not allow for a precise quantification of the total amount of driving done per day.		Fairly good study
					Sedentary and driving		2.2 (NS) / 0						
					Truck Driving		1.7 (p<0.02) / 20 (NS)						
					Driving		1.6 (NS) / 1.67 (NS)						
					Vibration non-driving		1.8 (p<0.02) / 0						
Froom, P., et al. (1984). **(C)**	Cross Sectional	153 Helicopter and 109 Transport Pilots (aged 26-35)	500 Cadets who had never flown (aged 18)							Prevalence of Lumbar Spondylolisthes is = 4.5% in helicopter pilots, vs. 1% in transport pilots, and 1% in cadets (p=0.08)	The four-fold increase of lumbar spondylolisthesis in helicopters pilots suggests that repetitive minor stresses without acute fracture can be causal. It is likely that vibrational forces are responsible for low back pain and the development of lumbar spondylolisthesis in a high percentage of helicopter pilots.		Helicopter pilots, might not be relevant
Petrovic, L. and Milosevic, M. (1985) **(C)**	Cross Sectional	44 Truck Drivers	376 Paper Workers and Carpenters, 66 Forest Woodcutters, 56 Bricklayers	Age, Length of Employment (stratified)			Lumbo-sacral Pain Prevalence:				Back pain prevalence was highest in the truck driver group, and had a tendency to increase with duration of employment, with the first cases appearing after 9 years on the job. Back pain increased with age in all four occupational groups.		
					Truck Drivers		29.40%						
					Paper Workers and Carpenters		10.90%						
					Forest Woodcutters		20%						
					Bricklayers		19.10%						
Brendstrup, T., and F. Biering-Sorensen (1987). **(A)**	Cross Sectional; Cohort	240 Male Fork-lift Truck Drivers, working ≥ 4 hours daily	399 Working Men from the same county; 66 Unskilled Workers, socially and economically matched	Age, Daily Hours Driving.			Point Prevalence: / Lifetime Prevalence / 1-Year				Low back trouble occurred more often among forklift drivers than among the controls. A correlation was found between length of employment as a forklift driver and low back pain. Low back trouble affected forklift drivers at an early age. 21% of forklift drivers left their job, many after 5 years. Age and daily driving hours were not significant variables in the multiple logistic regression analysis.		Fairly good, not overly
					Forklift Drivers		21% / 79% / 17%						
					Working Men		11% / 63% / 7%						
					Unskilled Labourers		8% / 64% / 3%						
					Years Driving Forklift (vs. < 3 years):		Relative Risk (some calculations from data):						
					3-5 years		7.0 *						
					6-10 years		9.1 *						
					> 10 years		13.6 *						
Dupuis, H. and G. Zerlatt (1987). **(C)**	Cross Sectional	352 Operators of Earth Moving Machines (exposed to vibration ≥ 3 years)	315 Unexposed Persons, exposed to similar working environments but not vibration	Age			Self-reported prevalence of disorders of the spine = 70%, vs 54% in controls, (p<0.01) / Self-reported prevalence of discomfort in the lumbar region = 68.7%, vs 41.6% in controls, (p<0.01)			Medically Examined Lumbar Syndrome Prevalence = 81% vs. 53% in controls (p<0.05)	Lumbar syndrome was the most frequent health impairment found among earth-moving machine operators. Cervical and thoracic damage was not significantly different than in controls. Radiological tests showed that morphological changes in the lumbar spine in earth-moving machine operators happenned earlier and at a higher rate than in the control group and the average population. Self-reported back pain increased with age.		Good Study, but lacks direct vibration level comparisons. Unable to tell what level of vibration is used for the earthmoving machines

Study Characteristics					Exposure Measurements		Outcome Measurements - Relative Risk (95% CI), except where otherwise noted				Conclusions		
Author (year)	Study Design	Subject Group	Control Group	Confounders Controlled For	Job Description	Vibration Exposure	Back Pain or Back Trouble	Sciatica	lumbar intervertebral	Other Outcomes		Comments	Heirarchy of Study Quality
Heliövaara, M. (1987). **(A)**	Case-Control	592 Men and Women with back problems	2,140 Men and Women without back problems, matched for age, sex, and residence	Occupational Activity, Self-reported Work Incapability, Work Load, Smoking, Chronic Cough, Symptoms Suggesting Psychic Distress, Use of Analgesics.	Male Motor Vehicle Drivers (Females results not reported)				2.9 * (p<0.05) relative risk of hospitalization (males only)	Sciatica or Herniated Disc: 4.6 * (p<0.05) relative risk of hospitalization (males only)	Male motor vehicle drivers had the highest risk of development of hospitalized herniated lumbar disc of all occupations in this study. Self-reported strenuousness of work did not predict herniated lumbar intervertebral disc or sciatica in men. Car driving may be aetiologically important for herniated discs. Women appeared to have a different distribution of occupations; driving among women was not reported.		Good study, no vibration measures though
Kompier, M., et al. (1987). **(C)**	Cross Sectional	158 Male Bus Drivers	2,728 Male Swedish Workers		Bus Drivers		Prevalence = 57% vs. 40% in Controls (p<0.001)				Musculoskeletal disorders in busdrivers increased with age until the last age period (41+), where they dropped off. A similar pattern was found for years of service and low back pain (rate dropped at 15+ years of service). Age and years of services were statistically significant determinants of musculoskeletal complaints. Self-reported vibration exopsure and poor ergonomics of the city bus cabin were related to musculoskeletal disorders.		Bad study, exposure to vibration not well defined, bus drivers in the subject and control group. I think we should remove it.
Saraste, H., and Hultman, G. (1987) **(C)**	Cross Sectional	1033 Swedish People with back pain	1839 Swedish People without back pain	Sex and Age Stratified: 30-39 years		Exposure to shaking or vibration at work:	Prevalence in Males with backp pain = 5% vs. 4% in those without (NS)				Physically heavy, bending and repetitive work was more common in those with back pain than those without. The oldest group had a higher proportion of smokers with back pain than without.		Okay study, exposure to vibration only yes/no.
				40-49 years			Prevalence in Males with backp pain = 13% vs. 2% in those without (p <0.001)						
				50-59 years			Prevalence in Males with backp pain = 5% vs. 3% in those without (NS)						
Bongers, P.M., et al. (1988a). **(A)**	Cohort Study	743 Male Crane Operators in Steel Company	662 Male Floor Workers in Steel Company, with similar social class	Age, Shift work, Nationality, Calendar Year			All back disorders, sickness absence ≥ 28 days or disability pension:		Sickness absence ≥ 28 days, physician confirmed or disability pension:	Discopathy, sickness absence ≥ 28 days or disability pension:	Crane operators with at least 5 years of exposure had significantly higher numbers of absences due to disease of the intervertebral disc. Although no difference between subjects and controls was found for all back disorders, the subject group had more and longer absenteeism due to the intervertebral disc disorders than the controls. Exposure to vibration and strained posture were considered to be responsible for the back disorders in the subject group.		This study may not be useful for this matrix, The diagnosis measure may be problematic.
					All Crane Operators		1.05 (0.72-2.45)* (90%CI)		1.7 (0.92-3.17)* (90%CI)	1.81 (0.95-3.45)* (90%CI)			
					≥ 5 years of work as a Crane Operator		0.98 (0.76-1.26)* (90%CI)		2.03 (1.05-3.94)* (90% CI)	2.19 (1.10-4.36)* (90%CI)			
Bongers, P.M., et al. (1988b). **(A)**	Retrospective Cohort Study *(same study as above, different*	743 Male Crane Operators in Steel Company	662 Male Floor Workers in Steel Company, with similar social class	Age, Shift Work	Years of employment as a crane operator: ≤ 4 years		Disability due to All Back Disorders: 0.23* (NS)		Disability due to Displacement of Intervetebral Disc: 0.23* (NS)	Disability due to Degeneration of Intervetebral Disc: 0.52* (NS)	The relative risk for total disability due to back disorders in the crane operators was 2.6. There was a 1.5-fold increase in risk of disability due to intervertebral disc disorders for each 10 years of additional exposure. Vibration acceleration levels ranging from 0.20-1.00 m/s^2 were considered at least partly responsible for serious back disorders. Disability due to		Good study, well done, some problems with loss to follow up, some of the statistics aren't clear.
					5 - 9 years		1.51* (NS)		1.72 * (NS)	3.23 * (p<0.05)			
					10 - 14 years		2.55* (p<0.01)		4.86 * (p<0.05)	6.54 * (p<0.05)			
					15 - 19 years		0.67* (NS)		-	2.04 * (NS)			

Author (year)	Study Design	Subject Group	Control Group	Confounders Controlled For	Job Description	Vibration Exposure	Back Pain or Back Trouble	Sciatica	lumbar intervertebral	Other Outcomes	Conclusions	Comments	Heirarachy of Study Quality
	different outcomes analyzed)				≥ 20 years		1.78* (NS)		16.9 * (NS)	5.73 * (p<0.01)	serious back disorders. Disability due to general back disorders was not different between the controls and the index group. It was not possible to adjust for strained sitting posture, adverse climate, and lifting and pulling on an individual basis in this study. Crane operators left their jobs due to the heavy workload, therefore the relative risks are considered unlikely to be overestimated.		
Netterstrom, B. and K. Juel (1989). **(C)**	Cross Sectional; Cohort	2,045 Male Bus Drivers	195 Coperhagen Motormen, Prevalence study.		Bus Drivers		Prevalence = 57% vs. 40 % in controls(p<0.05)				Urban bus drivers appeared to have a high incidence and prevalence of low back trauma. 6% of bus drivers over 50 left work due to back problems. Smoking and education were not significant variables. Psychosocial variables did not have a major influence on low back pain in this occupational group. Sedentary position and vibration exposure were assumed to be the most substantial factors influencing low back trouble.	.	Okay study, not a great deal of info.
		2,465 Male Bus Drivers	All Danish Men 1981, Incidence study.	Age, Calendar Year	Bus Drivers				1.37 (1.05-1.76)*				
Riihimaki, H., et al. (1989). **(C)**	Cross Sectional	Male Machine Operators exposed to vibration: 541 Longshoreman, 311 Earthmovers (aged 25 - 49)	674 Municipal Office Workers, 696 Carpenters	Age, Prior Back Accidents, Twisted Postures, Annual Car Driving.			1-Year Prevalence Lumbago: / 1-Year Prevalence Low-back trouble: / Lifetime Prevalence Low-back trouble:	1-Year Prevalence: / Relative 1-Year Prevalence:			Low back symptoms were more common among machine operators than carpenters. Occupation, age, posture, and previous back accident were significant variables in the multivariate analysis of the 1-year prevalence of sciatica. Annual car driving was not. Low back pain and sciatica increased with age. Office workers controls came from a different social class than subjects which may affect the occurrence of low back pain.		Fairly good study
					Machine Operators		24% / 82% / 90%	34% / 1.3 (1.1-1.7)*					
					Carpenters		25% / 79% / 90%	29% / 1.0 (0.8-1.3)*					
					Controls		18% (p<0.01) / 61% / 75% (p<0.01)	19% (p<0.001)					
Walsh, K., et al. (1989). **(C)**	Cross Sectional	436 Randomly Selected Residents of Whitechurch	Internal Reference Group	Walking or Standing for more than 2 h/d, Sitting for >2h/d, Driving a Car > 4 h/d, Driving a Truck, Tractor or Digger, Lifting or Moving Weights of 25 kg or more, Using Vibrating Machinery.			Lmbago, Occupation in prior year: / Lumbago, Lifetime occupation: / Unremitting Back Pain, Occupation in prior year:				Driving a car more than 4 h/day was associated with back pain for men, but not women (the number of women reporting was small). Truck, tractor, and digger driving was not associated with short-term back pain. Unremitting back pain showed the clearest relationships to occupational exposures. The fraction of disease attributable to car driving and heavy lifting is estimated to be 4% each. Heavy lifting had the strongest occupational association with low back pain.		okay study, slightly problematic with small n's and poor definitions. Confounding was oddly
					Driving a car > 4h/d: Male		1.7 (1.0-2.9)* / 1.2 (0.5-2.8)* / 2.2 (0.06-8.1)*						
					Female		0.4 (0.1-3.2)* / 0.8 (0.1-7.0)* / No Cases						
					Driving a truck, tractor or digger: Male		0.7 (0.4-1.4)* / 0.5 (0.2-1.0)* / 1.4 (0.4-5.1)*						
					Female		0.6 (0.1-5.2)* / 1.6 (0.1-16.6)* / 3.3 (0.3-41)*						
					Using Vibrating Machinery: Male		1.3 (0.7-2.4)* / 1.5 (0.7-3.1)* / 1.3 (0.3-5.2)*						
					Female		1.1 (0.1-9.4)* / 5.7 (1.1-29.3)* / 3.3 (0.3-41)*						
Bongers, P.M., et al. (1990). **(A)**	Cross Sectional	133 Helicopter Pilots	228 Non-Flying Pilots	Age, Height, Weight, Climate, Bending Forward, Twisted Posture, Feeling Tense.		All Pilots, mean dose = 774 hours x m^2/s^4	9.00 (4.9-16.4) (90% CI)	3.3 (1.3-8.5)* (90% CI)			Very high rates of back pain were found in young pilots. Duration and magnitude of vibration exposure were correlated, as were dose, daily exposure, and postural stress over the years. These factors complicate the assessment of the impact of specific exposure parameters. The occurrence of transient back pain appeared to be dependent on the duration of exposure. The health effects observed could be due to posture or vibration, but most likely the concomitant exposure to both factors. A significantly higher prevalence of back pain was observed only after a vibration dose of 400 hours x m^2/s^4. Transient low back pain may develop into chronic low back pain.		Well done, but its helicopter pilots and not drivers
						< 400 hours x m^2/s^4	12.0 (5.6-31.3) (90%CI)	1.4 (0.2-11.0)* (90% CI)					
						400-800 hours x m^2/s^4	5.6 (2.5-12.5) (90%CI)	1.5 (0.3-7.1)* (90% CI)*					
						800-1200 hrs x m^2/s^4	6.6 (2.9-15.1) (90%CI)	3.3 (1.1-10.0)* (90% CI)					
						> 1200 hours x m^2/s^4	39.5 (10.8-15.6) (90%CI)	5.6 (1.5-21.2)* (90% CI)					

Study Characteristics					Exposure Measurements		Outcome Measurements - Relative Risk (95% CI), except where otherwise noted					Conclusions		
Author (year)	Study Design	Subject Group	Control Group	Confounders Controlled For	Job Description	Vibration Exposure	Back Pain or Back Trouble		Sciatica	lumbar intervertebral	Other Outcomes		Comments	Heirarchy of Study Quality
Boshuizen, H.C., et al. (1990a). **(A)**	Cohort Study	798 Agriculture Workers	Internal Reference Group (storage, catering, technical, maintenance) with less exposure than 0.4 m/s^2 for 52 weeks	Age, Age^2, Height, Smoking, Twisting, Lifting, Mental Workload, Company			First Sick Leave ≥ 28 days for All Back Disorders				First Sick Leave ≥ 28 days for Disorders of the Intervertebral Disc:	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 are considered responsible for the increased incidence of back pain observed in tractor drivers. Sitting is not included in the analysis as sitting and driving were too closely correlated.		Good study, part of cohort Procedures not always Some of the study groups had small numbers. 166
						< 0.5 years x m^2/s^4	1 (reference)				1 (reference)			
						0.5-2.5 years x m^2/s^4	0.97 (0.59-1.61)* (90% CI)				4.1 (0.53-10)			
						2.5-5.0 years x m^2/s^4	1.51 (0.92-2.5)* (90% CI)				11 (1.7-267)			
						5 years x m^2/s^4	1.45 (0.84-2.5) (90% CI)				7.2 (0.92-179)			
Boshuizen, H.C., et al. (1990b). **(A)**	Cohort *(same study as above, different outcomes analyzed)*	577 Agriculture Workers who returned questionnaries in 1986	Internal Reference Group (storage, catering, technical, maintenance) with less exposure than 0.4 m/s2 for 52 weeks	Age, Age^2, Height, Smoking, Twisting, Lifting, Mental Workload, Company		0-5 years	2.44 (0.84-7.1)*		1.25 (0.36-4.4)*	4.0 (0.63-25)†		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.	Study Response was 79%. The effect of tractor	Excellent study
						5-10 years	2.5 (0.85-7.6)*		1.15 (0.31-4.2)*	5.3 (0.81-34)†				
						> 10 years	3.6 (1.21-11)*		1.42 (0.40-5.1*	6.8 (1.05-44)†				
						0.3-0.55 m/s^2	1.98 (0.97-4.0)*		1.68 (0.7-4.0)*	3.9 (0.94-17)†				
						0.55-0.7 m/s^2	1.66 (0.82-3.4)*		1.61 (0.69-3.7)*	3.5 (0.81-15)†				
						0.7-0.9 m/s^2	2.10 (1.07-4.1)*		1.60 (0.71-3.6)*	3.9 (0.91-16)†				
						>0.9 m/s^2	1.38 (0.52-3.7)*		3.0 (1.07-8.3)*	2.1 (0.35-13)†				
						0-2.5 years x	1.80 (1.11-2.9)†		1.36 (0.76-2.4)†	1.6 (0.62-4.0)†				
						2.5-5 years x	1.78 (1.04-3.1)†		1.69 (0.91-3.1)†	2.8 (1.15-6.9)†				
						> 5 years x m^2/s^4	2.8 (1.64-5.0)†		1.59 (0.84-3.0)†	2.7 (1.01-7.1)†				
Burdorf, A. and H. Zondervan (1990). **(C)**	Cross Sectional	33 Crane Operators in Steel Factory	30 Crane Helpers, General Operators, and Maintenance Workers in Steel Factory	Age, Height, Weight, Previous Exposure to Back Straining Work.			3.6 (1.2-10.6)*	1-Year Prevalence = 61% vs. 27% in controls	1-Year Prevalence = 27% vs. 10% in controls			The combination of twisting and bending the body in a sedentary position, and exposure to vibration is of greater importance to the occurrence of low back pain than dynamic work load. Previous exposure to back straining work, length of employment as a crane operator, age, height, and weight were not significant variables in the multiple regression model. Only 67% of crane operators responded; in the non-responders, there was an over-representation of long absence from work. Controls were taken from the factory, and thus excluded individuals on sick leave.		Okay study, analysis and statistics not that clear
Videman, T., et al. (1990). **(C)**	Cross Sectional	86 Male Cadavers < 64 years, employed before death, history of illness short	Internal Reference Group (analysis by type of work)	Age, Physical Loading						Anular Ruptures:	Disc Degeneratic	There is a progressive relationship between back pain and sciatica and physical workload. The most back pain was found for heavy or driving work. Driving was associated with the least symmetric disc degeneration, vertebral osteophytosis, and facet osteoarthrosis, all three being degenerative in character. There were more anular ruptures in driving occupations, confined to the lower intervertebral levels. Postural stress was considered a likely cause of back pain due to driving.		Strange study in that it
					Sedentary		0.14 (0.03-0.7)†		0.7 (0.2-1.9)†	1.0 (0.2-6.1)*	24.6 (1.5-409)*			
					Moderately Heavy		1 (reference)		1 (reference)	1 (reference	1 (reference)			
					Driving		2.3 (0.8-6.2)†		1.2 (0.5-3.4)†	2.9 (0.4-21.7)*	1.9 (0.2-20.3)*			
					Heavy Work		2.7 (1.1-6.2)†		1.9 (0.9-4.3)†	0.7 (0.1-4.6)*	2.8 (0.3-23.7)*			
Burdorf, A., et al. (1991) **(C)**	Cross Sectional	114 Male Concrete Manufacturing Workers	52 Male Maintenance Workers in an Engineering Factory	Age		Exposed to Whole-Body Vibration	3.06* (p<0.01)					Exposure to whole body vibration through the use of vibrotables was significantly related to low back pain among concrete workers. Posture was also significant, but age was not.		Okay Study, stats not very clear
					Concrete Machine Operators (64% work on Vibrotables)		Prevalence = 51%							
					Other Concrete Workers		Prevalence = 39%							
					Controls		Prevalence = 31%							

Study Characteristics					Exposure Measurements		Outcome Measurements - Relative Risk (95% CI), except where otherwise noted						Conclusions		
Author (year)	Study Design	Subject Group	Control Group	Confounders Controlled For	Job Description	Vibration Exposure	Back Pain or Back Trouble		Sciatica		lumbar intervertebral	Other Outcomes		Comments	Heirarachy of Study Quality
Heliövaara, M., et al. (1991). **(C)**	Cross Sectional	2,727 Men, 2,946 Women (aged 30-64)	Internal reference group (analysis by risk factor)	Sex, Age, Smoking, Alcohol, Mental Stress, Previous Back Injury, Height, Body Mass Index, Parity, Occupational History Occupational Stress (physical and mental).	Professional Driving		1.4 (1.0-2.0)† 1.1 (0.7-1.6)*		0.9 (0.5-1.6)† 0.7 (0.4-1.2)*				The risk of low back pain was significantly associated with professional driving, occupational physical stress (which included vibration as one of five variables), smoking, age, previous back injury, high levels of occupational mental stress. As the index of occupational physical stress increased, the risk of low back pain and sciatica increased. The determinants of sciatica and low back pain differed to some extent.		Fairly good study, (Calculation of this measure is not clear)
Johanning, E. (1991). **(C)**	Cross Sectional	492 Subway Train Operators	92 Tower Operators, with similar demographic characteristics, job histories and responsibility.	Age, Age^2, Gender, Job Title, Employment Duration.	Subway Train Operators		Prevalence = 56% vs. 36% in controls		3.9 (1.7-8.6)*			Medically-Confirmed Back-Problem Prevalence = 15% vs. 7% in controls	Subway train operators had a nearly four-fold increased risk of developing sciatica. The risk of sciatic pain did not increase with the duration of employment. The small size of this study or self-selection out of the workforce may be reasons for not seeing this relationship. The high risk for sciatica in this population may be a result of high lateral and vertical vibration exposures.		Fairly good study, very limited statistical analysis and nothing explicit done with vibration exposure
Nayha, S., et al. (1991). **(C)**	Cross Sectional	2,705 Reindeer Herders (using motorcycles and fourwheelers)	Internal reference group (analysis by work duration)	Age			1-Year Prevalence = 60% Self-Report, 20% Doctor Diagnosed		1-Year Prevalence = 32% Self-Report				Prevalence of all back pain and sciatica increased somewhat with number of days worked per year.		Might not be relevant
					year: ≤ 19		52.5%*		29.4%*						
					20 - 34		60.4%*		29.7%*						
					35 - 69		63.6%*		34.1%*						
					70 - 119		64.6%*		32.3%*						
					≥ 120		64.6%*		33.2%*						
Boshuizen, H., et al. (1992). **(A)**	Cross Sectional	242 Drivers of Forklifts and Freight Containers	210 Workers: Radio Dispatchers, Computer Operators, Security Guards, Stevedores and Others	Age, Height, Smoking, Mental Stress, Postures, Lifting, Looking Backwards, Hours Spent Sitting.			Back Pain:	Lumbago:	Sciatica, 1-Year				Young drivers, who also had low doses of vibration, had a higher prevalence of back pain than older drivers. This is likely due to a health-based selection process among older drivers, with those susceptible to back pain leaving the profession. Recent driving seemed to increase the risk of back pain, whereas driving more than 5 years prior to the onset of symptoms did not.		Good Study
					Driving Jobs (vs. Jobs Never driving)		2.2 (1.03-4.7)* (90% CI)	2.7 (1.08-6.9)† (90% CI)	1.06 (0.43-2.6)* (90% CI)						
						5 year x m^2/s^4 vibration dose, received <5 years before onset of Pain	2.4 (1.33-4.2)† (90% CI)	3.1 (1.23-7.9)†							
						5 year x m^2/s^4 vibration dose, received ≥5 years before onset of Pain	0.7 (0.53-0.94)† (90% CI)	0.8 (0.56-1.21)†							
Bovenzi, M. and A. Zadini (1992). **(A)**	Cross Sectional	234 Urban Bus Drivers with more than 5 years of employment (aged 26-55)	125 Maintenance Workers at the bus company with more than 5 years of employment (aged 26-55)	Age, Height, Weight, Education, Smoking, Sport Activity, Frequency of Awkward Postures at Work, Climatic Working Conditions, Perceived Mental Stress During Work, Previous Vibration Exposure and Previous Jobs with Heavy Work Demands.			Relative 1-Year Prevalence: p for trends < 0.05	Relative Lifetime Prevalence: p for trends < 0.05	Relative 1-Year Prevalence: p for trends < 0.05	Relative Lifetime Prevalence: p for trends < 0.05	Relative Lifetime Prevalence: p for trends (NS)		The prevalence of most low back pain increased with increasing total vibration dose. This study supports the hypothesis that the combination of vibration and postural stress plays an important role in the etiopathologies of lumbar spine disorders. Low back pain and leg pain increased with age in both subjects and controls. Awkward postures at work were also significantly related to some type of low back symptoms, but to a lesser extent than vibration. Low back pain occurred at vibration exposure levels that were lower than the health based exposure limits proposed by ISO 2631/1. The mean age of the bus drivers was significantly lower than the controls.		Very Good Study
						5-10 year	2.33 1.07-5.06)*	2.01 (0.94-4.3)*	2.14 (0.87-	1.87 (0.89-3.93)*	0.53 (0.12-				
						10-15 years	4.25 (1.9-9.5)*	4.40 (1.92-10.1)*	2.19 (0.97-4.94)*	1.67 (0.84-3.31)*	0.86 (0.24-2.99)*				
						>15 years	2.83 (1.4-5.75)*	3.54 (1.66-7.52)*	2.06 (0.93-4.53)*	1.86 (1.00-3.34)*	2.05 (0.81-				
						< 0.50 m/s^2	2.30 (0.99-	3.27 (1.39-7.71)*	2.76 (1.18-	2.09 (0.90-4.84)*	0.18 (0.02-				
						0.50-0.60 m/s^2	3.77 (2.01-	3.21 (1.64-6.25)*	1.37 (0.7-2.67)*	1.19 (0.62-2.27)*	0.67 (0.22-				
						>0.60 m/s^2	1.76 (0.86-	2.03 (0.95-4.34)*	2.26 (1.14-	2.54 (1.3-4.97)*	2.54 (0.95-				
						1.0-2.5 years x	1.67 (0.78-	1.66 (0.76-3.62)*	2.22 (1.02-	1.82 (0.85-3.23)*	0.48 (0.11-				
						2.5-4.5 years x	3.46 (1.8-6.62)*	3.34 (1.68-6.65)*	1.43 (0.72-	1.23 (0.63-2.39)*	0.66 (0.19-				
						> 4.5 years x m^2/s^4	2.63 (1.35-5.12)*	3.57 (1.72-7.40)*	2.28 (1.19-4.35)*	2.34 (1.25-4.39)*	2.61 (1.01-6.71)*				
Chernyuk, V.I. (1992) (C)	Cross Sectional	833 Tractors Drivers	Internal Reference Group		Years of employment:		Prevalence of Chronic Lumbago (Calculated from data):						The prevalence of chronic low back pain increased with years of both service as a tractor driver and estimated intensity of		

Study Characteristics					Exposure Measurements		Outcome Measurements - Relative Risk (95% CI), except where otherwise noted						Conclusions		
Author (year)	Study Design	Subject Group	Control Group	Confounders Controlled For	Job Description	Vibration Exposure	Back Pain or Back Trouble			Sciatica	lumbar intervertebral	Other Outcomes		Comments	Heirarachy of Study Quality
(C)			Group (analysis by years of employment and vibration intensity)		0 to 5		6.30%						tractor driver and estimated intensity of 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.		
					6 to 10		19.30%								
					11 to 20		21.40%								
					21 to 30		49.60%								
						110-112 dBeq	17.80%								
						113-115 dBeq	23.00%								
						116-118 dBeq	21.60%								
						119-121 dBeq	31.20%								
Miyashita, K., et al. (1992). **(C)**	Cross Sectional	184 Power Shovel Operators, 127 Bulldozer Operators, 44 Forklift Operators (aged 30 - 49)	44 Office Workers (aged 30 - 49)	Age			Prevalence:						This study suggests that the stress from vibration 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.		not a great study, confounders?
					Power Shovel		38% (NS)								
					Bulldozer		36.2% (NS)								
					Forklift		50% (p <0.05)								
					Office Worker (Control)		27%								
Pietri, F., et al. (1992). **(A)**	Cohort Study	1,719 Commercial Travelers (1376 Male, 343 Female)	861 Sedentary Workers	Sociodemographics, Life-style, Lifting and Standing at Work, Psychosomatic Factors.	Commercial Traveler, hours driving per week:		Relative Prevalence:	Relative 1-Year Cumulative Incidence:					Low back pain was associated with the number of hours spent driving and the comfort of the car seat. The role of the car seat cannot be clarified in this cross-sectional design. This study suggests there may be a threshold duration for the incidence of low back pain (10 h driving per week). A dose-response relationship was seen between the prevalence of low back pain and hours of driving. Tobacco consumption showed a significantly elevated risk for low back pain among current and ex-smokers as compared with non-smokers. No association was found with height, weight, education and low back pain.		Good Study, although the methods for the incidence study are not clear (I.e.
					10 to 14		1.5 (1.0-2.4)*	4.0 (1.1-14.3)*							
					15 to 19		1.2 (0.8-1.9)*	4.8 (1.4-16.4)*							
					20 to 24		2.0 (1.3-3.1)*	3.3 (0.9-12.0)*							
					≥ 25		2.1 (1.3-3.4)*	3.7 (0.9-14.0)*							
Burdorf, A. et al. (1993). **(C)**	Cross Sectional	94 Male Crane Operators, 95 Male Straddle Carrier Drivers	86 Male Office Workers	Age, Height, Weight, Occupational History, Psychological Stress, Climatic Conditions, Job Satisfaction.			Relative 1-Year Incidence:	1-Year Prevalence:					Occupational exposure to vibration was low (mean of 0.20 m/s^2). Sustained sedentary work in a non-neutral trunk posture was considered the most important risk factor for low back pain.		Study well done, but I thought they dismissed
					Crane Operators		3.29 (1.52-7.12)*	40% vs. 20% in Controls							
					Straddle Carrier Drivers		2.51 (1.17-5.38)*	31% vs. 20% in Controls							
Ruppe, K. and R. Mucke (1993) **(C)**	Cross Sectional	200 Male Drivers of Dumpers, Tractors, Earthmovers, in Construction and Agriculture	61 Unexposed Males, Locksmiths or Maintenance Workers, of similar age distribution.				Lifetime Prevalence = 100% vs. 34% in the controls					Prevalence of deviations of the lumbar spine = 55% vs. 1.6% of controls	Longlasting vibration exposure is able to cause strong disorders or injuries at the spine. Study found functional, neurological, and morphological disorders of the spine as a result of exposure. Radiographical findings were in good correlation with functional disorders. Vibration has the most influence on the thoracical and lumbar sections of the spine.		Health effects data done strangely, No exposure data, but this a recent German article (translated)
Bovenzi, M. and A. Betta (1994) **(A)**	Cross Sectional	1,155 Tractor Drivers	220 Revenue Officers	Age, Body Mass Index, Education, Marital Status, Sport Activity, Annual Car Driving, Climatic Conditions, Previous Jobs with Vibration Exposure, Heavy Physical Demands, Back Trauma, Postural Load.	Tractor Driving:		Chronic Low Back Pain:	Relative 1-Year Prevalence of Low Back Pain:	Relative Lifetime Prevalence of Low Back Pain:				The lifetime occurrence of low back pain and the period prevalence of several types of low-back symptoms were found to be greater in tractor drivers than in controls. The most serious low-back symptoms leading to chronic low back pain were associated with prolonged tractor driving experience, which resulted in a high accumulated vibration dose. Duration of exposure to vibration was related to low back pain more than equivalent vibration magnitude. Awkward posture was also an important predictor of low back pain among the tractor drivers. There was an		Good study
					5-15 years		1.56 (0.92-	2.65 (1.68-4.18)*	3.08 (1.88-	3.70 (1.57-8.69)*	1.79 (0.48-				
					16-25 years		1.87 (1.10-	2.31 (1.46-3.64)*	3.03 (1.8-	3.90 (1.69-9.02)*	2.40 (0.72-				
					> 25 years		2.13 (1.21-	2.74 (1.69-4.45)*	4.51 (2.43-	4.46 (1.86-10.7)*	2.85 (0.82-				
						0.5-1.0 m/s^2	1.58 (0.94-	2.39 (1.52-3.76)*	2.81 (1.70-	3.15 (1.36-7.29)*	2.04 (0.74-				
						1.0-1.25 m/s^2	1.84 (1.10-	2.87 (1.83-4.49)*	3.64 (2.23-	4.68 (2.06-10.6)*	1.28 (0.46-				
						>1.25 m/s^2	1.78 (1.04-	2.29 (1.43-3.68)*	3.42 (2.00-	3.65 (1.56-8.53)*	2.24 (0.81-				
						<15 years x m^2/s^4	1.48 (0.87-	2.33 (1.48-3.67)*	2.79 (1.70-	2.92 (1.24-6.89)*	1.95 (0.68-				
						15-30 years x	1.90 (1.13-	3.04 (1.92-4.82)*	3.44 (2.05-	4.74 (2.07-10.8)*	1.41 (0.50-				

Study Characteristics					Exposure Measurements		Outcome Measurements - Relative Risk (95% CI), except where otherwise noted				Conclusions		
Author (year)	Study Design	Subject Group	Control Group	Confounders Controlled For	Job Description	Vibration Exposure	Back Pain or Back Trouble	Sciatica	lumbar intervertebral	Other Outcomes		Comments	Heirarachy of Study Quality
						>30 years x m^2/s^4	2.00 (1.17-3.40)* 2.36 (1.48-3.74)* 3.79 (2.20-6.53)*	4.14 (1.78-9.61)*	2.05 (0.76-5.54)†		increasing low back pain prevalence with increasing postural load in both tractor drivers and controls. Tractor driving is significantly related to an increased risk for low-back symptoms. Both total vibration dose and awkward postures were predictive factors when controlled for confounders.		
Masset, D. and J. Malchaire (1994). **(B)**	Cross Sectional	618 Blue Collar Steel Workers (aged < 40)	Internal Reference Group (analysis by duration of driving)	Age, Seniority, Height, Weight, General Health, Chronic Diseases, Accidents, Personality, Smoking, Sports, Satisfactions with Family and Occupation, Abnormal Fatigue, Depressive Tendency, Irritated Temper, Headache.	each 2-fold increase in duration of Industrial Vehicle Driving		Relative 1-Year Prevalence: 1.15 (p < 0.005)*				Vehicle driving was significantly related to low back pain, but self-reported vibration exposure was not. This may be a result of workers' differing perceptions of past exposures to vibration. No correlation was found between vehicle driving and vibration exposure. Heavy efforts of the shoulders and seated posture were significant in the multiple regression analysis, whereas lifting, repetitive movements, and constrained postures were not.		Pretty good study
Riihimaki, H., et al. (1994). **(B)**	Cohort Study *(follow-up of previous study group, from Riihimaki, H., et al. (1989))*	387 Machine Operators (Earth Mover Operators, Longshoremen in Motorized Stevedoring), all without sciatica in 1984 (ages 25-49)	426 Office Workers, 336 Carpenters, all without sciatica in 1984 (ages 25-49)	Seniority, Smoking, Physical Exercise, Amount of Twisted Posture, High Pace of Work, Workmate Problems, Draft, Cold, Vibration, Back Accidents, Other Low Back Pain	Machine Operators Machine Operators Carpenters Office Workers	 Vibration-exposed		3-year Cumulative Incidence: 22% 1.36 (0.99-1.87)* 1.33 (0.85- 24% 1.50 (1.09- 14%			Men in dynamic physical work and machine-operating work had a higher risk of sciatic pain than office workers. Complaint of vibration was a non-significant predictor of 3 -year cumulative incidence of sciatic pain among machine operators. When history of low back pain was removed from the model, vibration became a significant predictor (RR=1.53, 95% CI = 0.98-2.39). Previous Injury and smoking also increased the risk of sciatica.		Pretty good study
Barbieri, G., et al. (1995). **(C)**	Cross Sectional	29 Male Tractor Drivers with > 5 years of employment.	100 Unexposed Males, with similar weight, height, and age.	Age (Stratified)						Comparison between head and trunk movement of subjects and controls shows a significant reduction of tractor drivers' spinal mobility in both age strata (36-45, 46-55)	The reduction of spine mobility in the tractor drivers could be attributed to occupational posture and vibration. Tractor drivers' posture causes considerable load for the lumbar spine and increases vibration transmission. Long term occupational driving is a risk for the spine. The transmission of road shocks, vertical impacts, and cooling may contribute to the action of incorrect posture and vibration on spinal mobility.		Okay study, procedures not totally clear, but sn interesting measure It is unclear if measurements on vibration levels of the tractors corresponded to the tractors used by the study group. The process for selecting subjects is unclear.
Guo, H-R., et al. (1995) **(C)**	Cross Secional	5,256 workers with back pain from the US National Health Interview Survey	24,818 other wokers from the US National Health Interview Survey	Sex (stratified) and Weighting to Structure of US Population (incompletely described)	Male Drivers: Industrial truck and tractor equipment Heavy Trucks Light Trucks		 2.0 1.7 1.6				Driving occupations were 3 of the 15 highest risk occupations for back pain in men (of 49 major occupations). Driving was not reported as a high risk occupation for women; it is not possible to determine whether this is because driving was not one of the 45 major occupations for women, or because it was not high risk.		
Jensen, M.F. (1996). **(A)**	Cohort Study	89,146 Male Professional Drivers (aged 15-59)	1.3 million Employed Swedish Males (aged 15-59)	Age, Calendar Year.	All Drivers Drivers doing Heavy Lifting					Prolapsed Cervical Disc: 1.42 (1.26- 1.37 (1.19-1.57)*	Professional driving was a risk factor for prolapsed cervical intervertebral disc. There was no indication that carrying heavy loads led to an increased risk of prolapsed discs. This study supports the hypothesis that prolapsed discs may result from		Fairly good, nice distinction between heavy

Study Characteristics					Exposure Measurements		Outcome Measurements - Relative Risk (95% CI), except where otherwise noted				Conclusions		
Author (year)	Study Design	Subject Group	Control Group	Confounders Controlled For	Job Description	Vibration Exposure	Back Pain or Back Trouble	Sciatica	lumbar intervertebral	Other Outcomes		Comments	Heirarachy of Study Quality
					Drivers with Little Heavy Lifting					1.84 (1.37-2.46)* relative risk of hospitalization	vibration exposure. The relative prevalence of vibration exposure among drivers was 7.1 (4.1-11.7), greater than the relative prevalence of heavy lifting of 1.8 (1.3-2.4).		
Liira, J., et al. (1996) **(B)**	Cross Sectional	18,920 Ontario Residents (aged 16-64)	Internal Reference Group (analyzed by occupational risk factors)	Age, Sex, Smoking	White Collar: Driving Operating vibrating vehicles or equipment Blue Collar: Driving Operating vibrating vehicles or equipment		1.15 (0.71-1.86)* 1.71 (1.09-2.67)* 1.28 (0.89-1.84)* 1.84 (1.25-2.72)*				Blue collar workers experienced more back pain than white collar workers. Age, smoking, white collar/blue collar, bending and lifting, working in an awkward posture, and operating vibrating vehicles or machines were all significant predictors of back pain. Study concludes that one quarter of the excess back pain in Ontario's working population is due to bending and lifting, working with vibrating equipment, or working in awkward postures.		
Magnusson, M.L., et al. (1996). **(C)**	Cross Sectional	111 Male Bus Drivers, 117 Male Truck Drivers	137 Male Sedentary	Age, Height, Weight, Work Satisfaction, Stress, Living Habits, Social Status, Work Environment, Posture on the Job, Psychosocial Factors.	Drivers Bus Drivers Truck Drivers	Long-Term 4.13 hours x m/s^2 48.2 yrs x hrs x m/s^2 6.04 hours x m/s^2 80 yrs x hrs x m/s^2	1.79 (1.16-2.75)* 2.0 (0.98-4.1)* Prevalence = 60% vs. 42% in Controls Prevalence = 56% vs. 42% in Controls				The highest risk factors for low back pain were vibration exposure, heavy lifting, and frequent lifting. Daily vibration exposure did not relate to reporting back pain but those who reported low back pain had a significantly higher total long-term vibration exposure that those who did not report this pain. Long-term vibration exposure was the strongest predictor of length of sick leave due to low back pain.		Okay Study, not extremely
Xu, Y., et al. (1997) **(C)**	Cross Sectional	5,185 randomly sampled members of the Danish population who were employed in 1990 (aged 18 - 59)	Internal reference group (analysis by risk factor)	Sex, Age, Education, Duration of Employment, Occupation		Self-reported vibration Seldom 1/4 of the time 1.2 of the time 3/4 of the time All the time	1.23 * (NS) 1.28 (1.0 - 1.0 (reference) 1.60 1.17 1.00 1.78 (p for trend = 0.009)				This study found a slight increase in risk of back pain with self-reported vibration exposure, and this increased with daily duration of exposure. Other significant risk factors included physically hard work, twisting and bending, standing up, and concentration demands.		
Thorbjörnsson, C.O.B., et al. (1998) **(C)**	Cross Sectional; Cohort	252 Women, 232 Men (aged 42-58) without musculo-skeletal diagnosis in a 1969 study of a population from Stockholm county.	Internal reference group (analysis by risk factor)	Age, Previous Low Back Pain		Self-reported vibration Men	Relative Prevalence: 1.3 (0.8-2.0)* Relative Incidence (1969-1993): 1.4 (1.1-1.8)*				This study found a slight increase in risk of back pain with self-reported vibration exposure in men. The were too few women with vibration exposure to allow analysis. High physical load, full-time work, unsatisfactory leisure time, few social contacts, and additional domestic work were also risk factors.		

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, probabilty 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

Author (year)	Industry; Study Conditions; Study Objectives	Measurement Location; Device Type; Sample Duration	Vehicle Types	Vehicle Specifics	Vibration Exposure Levels (Exposure in Root Mean Square m/s^2 unless otherwise specified)	Dominant Vibration Frequencies (Hz)	Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)	Peak Exposure or Crest Factors (CF, a_{peak}/a_{rms})	Jolts and shocks	Determinants of Vibration Exposure (other than vehicle type)
[Heino, Ketola, Makela, Makinen, Niemela, Starck, and Partanen, 1978]	Locomotive engineers; Mostly with loco's running on main tracks; Exposure assessment.	At seat; Tri-axial accelerometers; Sample duration 0.5 – 2 hr.	35 locomotives of 15 different types (3 categories based on power source and cab position).	Electric, cab at both ends Diesel, center cab Diesel, cab at both ends	NR[i]	In general, highest components of z-axis vibration were at 2 – 4 Hz.	72 % of measurements > EL[ii] 19 % of measurements > EL 24 % of measurements > EL	NR	NR	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.
[Howat, 1978]	Forestry Vehicles; Dry-land sort; Exposure assessment.	Seat; Z-axis only; 15 minute sample.	Caterpillar logging vehicles.	Caterpillar 966 (Manuf. 1973) Caterpillar 966 (Manuf. 1977) Caterpillar 980 Caterpillar 988	Exceeds 1 m/s^2 ~95% of observations Exceeds 1 m/s^2 ~65% of observations Exceeds 1 m/s^2 ~55% of observations Exceeds 1 m/s^2 ~15% of observations	NR	98% obs > 8hour ISO FDP 92% obs > 8hour ISO FDP 92% obs > 8hour ISO FDP 25-55% obs > 8hour ISO FDP	NR	NR	Work rate
[Hansson and Wikstrom, 1981]	Forestry equipment operators; Road and off road Conditions; comparing subjective evaluation with objective measurements.	At seat; Tri-axial measurements; Samples < 4 minutes.	Off-road forestry vehicles; 42 drivers.	5 different vehicles.	$a_{vector\ sum}$ = 0.18 – 1.78 m/s^2	z-axis = 1.5 – 3.0 Hz	NR	Crest factors in range 3-7	NR	Speed, surface smoothness and terrain
[Redmond and Remington, 1986]	Coal Mining; Normal operating conditions; Exposure assessment study.	At seat; Tri-axial accelerometers; 12 - 18 minute samples.	Surface and underground vehicles (N=86 samples).		NR	NR	Probablity (%) of exceeding ISO 2631 EL in: Any axis "Z-Axis"	NR	NR	NR
				Surface machines:						
				Bulldozers			33.8 13.3			
				Scrapers			42.5 22.0			
				Haulers (off-highway)			17.6 14.2			
				Highway trucks			8.8 8.5			
				Loaders			31.1 10.6			
				Blast hole drills			0.0 0.0			
				Motor graders			01.0 0.0			
				Shovels and draglines			0.0 0.0			
				Underground:						
				Continuous miner			2.0 2.0			

Author (year)	Industry; Study Conditions; Study Objectives	Measurement Location; Device Type; Sample Duration	Vehicle Types	Vehicle Specifics	Vibration Exposure Levels (Exposure in Root Mean Square m/s^2 unless otherwise specified)	Dominant Vibration Frequencies (Hz)	Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)	Peak Exposure or Crest Factors (CF, a_{peak}/a_{rms})	Jolts and shocks	Determinants of Vibration Exposure (other than vehicle type)
Redmond and Remington, Cont'd				Personnel carrier Haulage vehicle Bridge conveyor			6.0 6.0 22.0 18.0 NR 0.0			
[Bongers, Boshuizen, Hulshof and Koemeester, 1988a]	Crane operators; Operating conditions NR; Health Study	"In agreement with ISO 2631 guidelines".	Crane Operators.	Crane operators	a_{wz} = 0.25 - 0.67 m/s^2	NR	NR	NR	NR	NR
[Netterstrom and Juel, 1989]	Bus drivers; Operating conditions NR; Health Study.	NR	Bus Drivers.	Bus Drivers	105 dB	Acceleration given for 3 - 20 Hz range.	NR	NR	NR	NR
[Village, Morrison and Leong, 1989]	Mining; Normal operating conditions; Exposure assessment.	At seat; Tri-axial accelerometers; Sampled over set of standard tasks.	Load-haul-dump vehicles (N=22 samples).	8 yd capacity 6 yd capacity 5 yd capacity 3.5 yd capacity	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	20/22 sets of measurements exceed ISO 2631; 90% of vehicles exceeded EL_x and EL_z; 52% exceeded EL_y. Using ISO task-based scheme, all samples > EL.	Peaks range from 1.2 to 20 m/s^2, but no consistent pattern[iii]. 76% (mine A), 43% of samples (mine B) exceeded crest factor of 6.	Drivers exposed to random jolts of > 20 m/s^2, well in excess of ISO 2631. Operators leave seat, creating additional impact forces.	Significant differences between vehicle sizes and tasks, also vehicle/task interaction; Other potential determinants: road conditions, tire type, size and pressure, seating suspension.
[Boshuizen, Hulshof and Bongers, 1990]	Agricultural vehicles; Normal working conditions; Health Study.	Measurement location NR; Triaxial accelerometer; Sample duration NR.	Tractors, bulldozers, combine harvesters, lorry, van and car.	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	$a_{vector\ sum}$ = 0.50-0.59 $a_{vector\ sum}$ = 1.47 $a_{vector\ sum}$ = 0.67-0.98 $a_{vector\ sum}$ = 1.17 $a_{vector\ sum}$ = 1.76-2.03 $a_{vector\ sum}$ = 0.52-0.64 $a_{vector\ sum}$ = 0.43-0.80 $a_{vector\ sum}$ = 0.28 $a_{vector\ sum}$ = 0.78 $a_{vector\ sum}$ = 0.37 $a_{vector\ sum}$ = 0.25					

Author (year)	Industry; Study Conditions; Study Objectives	Measurement Location; Device Type; Sample Duration	Vehicle Types	Vehicle Specifics	Vibration Exposure Levels (Exposure in Root Mean Square m/s^2 unless otherwise specified)	Dominant Vibration Frequencies (Hz)	Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)	Peak Exposure or Crest Factors (CF, a_{peak}/a_{rms})	Jolts and shocks	Determinants of Vibration Exposure (other than vehicle type)
[Bongers, Hulshof, et al, 1990]	Helicopter pilots; Representative flight conditions; Health study.	Measurement location NR; Triaxial accelerometer; Sample duration NR.	4 Helicopter types, two vehicles of each type measured.	Alouette III	a_{wx}=0.12-0.17, a_{wy}=0.17-0.25, a_{wz}=0.44-0.67 $a_{vector\ sum}$ = 0.56-0.75	x, y, z = 16	FDP reached at 2-4 hrs at a_{vs}	NR	NR	NR
				Bolkow 105	a_{wx}=0.09-0.13, a_{wy}=0.13-0.18, a_{wz}=0.29-0.49 $a_{vector\ sum}$ = 0.36-0.58	x, z = 25, y = 6	FDP reached at 3-7 hrs at a_{vs}			
				Sikorsky 61	a_{wx}=0.06-0.11, a_{wy}=0.10-0.21, a_{wz}=0.17-0.44 $a_{vector\ sum}$ = 0.24-0.55	x, y = 16, z=8	FDP reached at 4-13 hrs at a_{vs}			
				Sikorsky 76	a_{wx}=0.07-0.14, a_{wy}=0.10-0.19, a_{wz}=0.17-0.36 $a_{vector\ sum}$ = 0.28-0.45	x, y = 20, z=8	FDP reached at 5-10 hrs at a_{vs}			
[Griffen, 1990]	Road and agricultural vehicles; Normal operating conditions; Exposure assessment.	Seat; Triaxial accelerometer; 15-30 minute samples.	Various road and agricultural vehicles.			NR	Exceed FDP after / Exceed EL after	Crest Factor (Z-axis)	NR	Road surface
				Autos, and Vans (n=11)	a_{wz} = 0.25 – 1.00		- / -			
				Truck	a_{wz} = 0.40 – 1.75		- / -			
				Buses (n=3)	a_{wz} = 0.60 – 1.30		- / -			
				Auto (city road)	$a_{vector\ sum}$ = 0.43		5 hours / 15 hours	4.8		
				Van Country road	$a_{vector\ sum}$ = 0.89		2 hours / 5 hours	5.7		
				Truck Rough road	$a_{vector\ sum}$ = 1.06		1.5 hours / 4 hours	3.9		
				Tractors, mowing	$a_{vector\ sum}$ = 1.20		1 hours / -	6.3		
				Tractors, hay turning	$a_{vector\ sum}$ = 2.00		40 minutes / -	8.5		
				Tractors, farm road	$a_{vector\ sum}$ = 2.24		15 minutes / -	4.2		
[Johanning, Wilder, Landrigan, and Pope, 1991]	Subway trains; Normal operating conditions; Exposure assessment.	At seat; Tri-axial accelerometer; Approx. 2 hrs of data.	Old (1948) to new (1988) subway cars.		Mean of all car types: $a_{vector\ sum}$ = 0.55 (range 0.32 – 0.99) a_{wx} = 0.10 a_{wy} = 0.26 a_{wz} = 0.37	1 – 2 Hz (lateral) 2.5 and 12.5 Hz (Vertical)	Using vector sum averages, concluded operators should not be exposed more than an average of 3.75 hours/day (based on FDP).	NR	NR	Suggest inter-car differences based on: Track conditions, train speed, vehicle maintenance, driving style.
					Specific car types:					
				R10 cars (manuf. 1948)	a_{xw} = 0.10; a_{yw} = 0.21; a_{zw} = 0.33					
				R68 cars (manuf. 1988)	a_{xw} = 0.08; a_{yw} = 0.19; a_{zw} = 0.29					
[Boshuizen, Bongers, Hulshof, 1992]	Heavy Equipment; Normal working conditions; Health study.	At seat; Tri-axial accelerometer; Sample duration approx. 5 min.	2 forklifts and freight tractor.	Small forklift	$a_{vector\ sum}$ = 0.80 m/s^2	3.15 Hz	Acceleration levels for forklifts exceeded FDP 4 hour limit; levels for tractor exceeded 2.5 hour limit.	Crest factors all above 6.	NR	NR
				Large forklift	$a_{vector\ sum}$ = 0.79 m/s^2	2.5 Hz				
				Freight container tractor	$a_{vector\ sum}$ = 1.04 m/s^2	1.6, 2.5 Hz				

Author (year)	Industry; Study Conditions; Study Objectives	Measurement Location; Device Type; Sample Duration	Vehicle Types	Vehicle Specifics	Vibration Exposure Levels (Exposure in Root Mean Square m/s^2 unless otherwise specified)	Dominant Vibration Frequencies (Hz)	Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)	Peak Exposure or Crest Factors (CF, a_{peak}/a_{rms})	Jolts and shocks	Determinants of Vibration Exposure (other than vehicle type)
[Bovenzi and Zadini, 1992]	Bus Drivers; Actual driving conditions; Health study.	Seat; Triaxial accelerometer; 15-30 minute samples.	Older Fiat buses (manuf. 1968-1973), Newer Inveco and Inbus buses (manuf. 1987-1990).	Fiat 409 DSU Fiat 410 P Fiat 418 AL Invbus U-210 FTN Iveco U-F1 Iveco Turbocity-U	a_{wx} = 0.12, a_{wy} = 0.16, a_{wz} = 0.65, $a_{sb,wx}$ [iv] = 0.15 $a_{vector\ sum}$ = 0.71 [v] a_{wx} = 0.10, a_{wy} = 0.12, a_{wz} = 0.40, $a_{sb,wx}$ = 0.17 $a_{vector\ sum}$ = 0.46 a_{wx} = 0.11, a_{wy} = 0.12, a_{wz} = 0.59, $a_{sb,wx}$ = 0.17 $a_{vector\ sum}$ = 0.63 a_{wx} = 0.08, a_{wy} = 0.08, a_{wz} = 0.29, $a_{sb,wx}$ = 0.14 $a_{vector\ sum}$ = 0.33 a_{wx} = 0.09, a_{wy} = 0.06, a_{wz} = 0.18, $a_{sb,wx}$ = 0.15 $a_{vector\ sum}$ = 0.24 a_{wx} = 0.09, a_{wy} = 0.05, a_{wz} = 0.22, $a_{sb,wx}$ = 0.10 $a_{vector\ sum}$ = 0.24	NR	NR	NR	NR	Authors comment that seat suspension in old Fiat buses (transmissibility, $T=a_{zw,seat}/a_{zw,floor}$) varied from 1.6 to 1.9, while in newer Inbus and Inveco buses T = 1.1 to 1.25.
[Piette and Malchaire, 1992]	Steel works; Normal operating conditions; Determinants of exposure analysis.	At seat and floor; Tri-axial accelerometers; 2 minute samples.	70 Cranes.	Mid-span cab End cab	a_{gw} = 0.37 – 1.16 [vi] a_{gw} = 0.26 – 1.03	Peaks found at 4 – 8 Hz	6/21 cranes in excess of FDP; none above EL.	NR	Shocks apparent from time-traces of Z-axis measurements (Fig 5).	Crane span, load, runway condition, cabin position, suspension, seat, speed.
[Burdorf, Naaktgebore, and de Groot 1993]	Port workers; Variety of working conditions; Health study.	Measurement location NR; Tri-axial accelerometers; 5 min samples.	20 Cranes, 21 straddle carriers.	Cranes Straddle carriers	a_{wx} = 0.15, a_{wy} = 0.11, a_{wz} = 0.17 a_{wx} = 0.18, a_{wy} = 0.16, a_{wz} = 0.22	NR	NR	NR	NR	NR
[Burdorf and Swuste, 1993]	Professional Drivers; Normal working conditions; Study of attenuation efficiency of suspension seats.	Seat and Floor; Tri-axial accelerometer but study limited to a_{zw}; sample duration 5 min.	Lorries Fork lifts Tractors.	Lorries Fork lifts Tractors	a_{wz} = 0.50 – 0.99 a_{wz} = 0.55 – 0.89 a_{wz} = 0.36 – 0.92	1.15 – 2.7 Hz	All worksites measurements exceeded 8hr ISO 2631 FDP level, and 9/24 worksites exceeded EL.	NR	NR	Seat suspension characteristics: Mean Seat transmissibility ($T=a_{zw,seat}/a_{zw,floor}$) varied from 0.34 – 1.28 [vii].
[Anttonen and Niskanen, 1994]	Reindeer herding; Typical working conditions; Exposure assessment.	At seat and foot board; Tri-axial accelerometers; Sample duration 10 – 50 minutes.	Snowmobiles: Old (1974) to New (1993) designs.	1983 seat 1983 frame 1988 seat 1988 frame 1994 seat 1994 frame	$a_{vector\ sum}$ = 1.5 [viii] $a_{vector\ sum}$ = 1.0 $a_{vector\ sum}$ = 1.2 $a_{vector\ sum}$ = 2.8 $a_{vector\ sum}$ = 3.0 $a_{vector\ sum}$ = 3.3	2, 6 Hz 4, 40 Hz 2, 20 Hz 10, 63 Hz 2 Hz 8 Hz	Majority of measurements exceeded proposed European standards (0.7 m/s^2, ceiling value).	NR	Shocks considered high risk for snowmobilers.	Seat resonance (i.e. amplifying rather than attenuating frame vibration), uneven terrain, speed.

Author (year)	Industry; Study Conditions; Study Objectives	Measurement Location; Device Type; Sample Duration	Vehicle Types	Vehicle Specifics	Vibration Exposure Levels (Exposure in Root Mean Square m/s^2 unless otherwise specified)	Dominant Vibration Frequencies (Hz)	Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)	Peak Exposure or Crest Factors (CF, a_{peak}/a_{rms})	Jolts and shocks	Determinants of Vibration Exposure (other than vehicle type)
[Bovenzi and Betta, 1994]	Tractors; Normal operating conditions; Health study.	At seat; Tri-axial accelerometer; Sampling duration NR.	Low-power tractors (45-85 hp).	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	$a_{vector\ sum}$ = 1.24 (mean, range = 0.58-2.00) $a_{vector\ sum}$ = 0.96 (mean, range = 0.36-2.03) $a_{vector\ sum}$ = 0.89 (mean, range = 0.53-1.25) $a_{vector\ sum}$ = 1.08 (mean, range = 0.85-1.30) $a_{vector\ sum}$ = 1.05 (mean, range = 0.86-1.25) $a_{vector\ sum}$ = 1.41 (mean, range = 0.84-1.82)	2.5 - 4 Hz	For estimated daily average exposure (2.7 hours), mean value of frequency weighted acceleration is below EL.	NR	NR	NR
[Ozkaya, Willems and Goldsheyder, 1994]	Subway trains; Normal operating conditions; Exposure assessment.	At seat; Tri-axial accelerometer; 48 round trips giving 100 hours of data.	Subway car .	16 different types	Average acceleration (by subway line) ranging from 0.37 m/s^2 to 0.57 m/s^2	NR	Exposure levels above ISO 2631 FDP on 6/20 lines; none over EL.	NR	NR	Speed, track type and condition, car type, maintenance, passenger load, driver experience.
[Barbieri, Mattioli, Grillo, Geminiani, Mancini and Raffi, 1995]	Tractors; Operating conditions NR; Health study.	NR	Agricultural tractors.	Agricultural tractors	50% of tractors acceleration between 1.16 m/s^2 and 1.93 m/s^2	z = 4.5	FDP exceeded in between 21 and 58 minutes at 1.16 m/s^2 and 1.93 m/s^2 respectively.	NR	NR	NR
[Suvorov, Starozhuk, Tseitlina, and Lagutina, 1996]	Heavy equipment; Conditions NR; Exposure assessment.	Measurement location NR; Device type NR; Summary data of 10,000+ obs.	Heavy equipment – 90 different vehicle types.	Tractor Bulldozers Open Mine Excavator Drill Rig	69 dB[ix] 69 dB 60 dB 58 dB	NR	NR	NR	NR	NR
[Ozkaya, Goldsheyder and Willems, 1997]	Subway trains; Normal operating conditions; Exposure assessment.	At seat; Tri-axial accelerometer; Sample duration between 43 and 660 sec.	2 new-technology subway trains.	"A-line", new car "A-line", old car "2-line", new car "2-line", old car	a_{zw} = 0.18; $a_{vector\ sum}$ = 0.38 a_{zw} = 0.27 – 0.34; $a_{vector\ sum}$ = 0.51 – 0.53 a_{zw} = 0.12; $a_{vector\ sum}$ = 0.26 a_{zw} = 0.20; $a_{vector\ sum}$ = 0.38	NR	Older cars both exceed FDP boundary; new car only 23% of FDP boundary.	NR	NR	Suspension, air better than springs.
[Robinson, Martin, Roddan, Gibbs, and Dutnall, 1997]	Mining; Typical operating conditions; Exposure assessment for return to work planning.	At seat; Tri-axial measurements; Sampling duration NR.	Representative sample of mine equipment.	Heavy Trucks Light Trucks Earth Movers	a_z = 0.7 – 1.0 a_z = 1.0 – 2.0 a_z = 0.7 – 1.0		All vehicles > ISO 2631 FDP_{8hr}. Range of Vibration Dose Value (VDV)[x] = 13 – 33 $m/s^{1.75}$.	CF_z = 7.8 – 18.8 CF_z = 7.4 – 17.5 CF_z = 10.6 – 24.0 Total of 8 of 11 vehicles CF > 10		Vehicle and roadway maintenance.

Author (year)	Industry; Study Conditions; Study Objectives	Measurement Location; Device Type; Sample Duration	Vehicle Types	Vehicle Specifics	Vibration Exposure Levels (Exposure in Root Mean Square m/s^2 unless otherwise specified)	Dominant Vibration Frequencies (Hz)	Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)	Peak Exposure or Crest Factors (CF, a_{peak}/a_{rms})	Jolts and shocks	Determinants of Vibration Exposure (other than vehicle type)
[Futatsuka, Maeda, Inaoka, Nagano, Shono, and Miyakita, 1998]	Agricultural equipment; Normal working conditions; Exposure assessment.	At seat; Tri-axial measurements; Each vehicle tested on 4 runs, each of 30 sec duration.	Common agricultural equipment: combines, tractors, other specialized equipment.	Combine (Iseki HL3700) Combine (Iseki 197) Combine (Yanmar TC 2200M) Tractor (Kubota MI 46) Hinomoto (NX 23) Riding rice power Transplanter Farm Carrier Cultivator Tea leaf plucker	$a_{vector\ sum}$ = 0.41 $a_{vector\ sum}$ = 0.57 $a_{vector\ sum}$ = 1.03 $a_{vector\ sum}$ = 0.89 $a_{vector\ sum}$ = 0.43 $a_{vector\ sum}$ = 0.35 $a_{vector\ sum}$ = 0.59 $a_{vector\ sum}$ = 1.00 $a_{vector\ sum}$ = 0.54 $a_{vector\ sum}$ = 1.63	NR	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.	NR	NR	NR
[Holmlund and Lundstrom, 1999]	Heavy Equipment; Normal working conditions; exposure assessment.	NR	Several heavy equipment types (N=57).	Band Excavator (e.g. D5 Cat) Dumper (e.g. Volvo DR 860) Excavator (e.g. Cat 225 LC) Loader (e.g. Cat 966) Grader (e.g. Cat 140) Tractor Excavator (e.g. Ford 550)	$a_{vector\ sum}$ = 1.84 (range = 1.50 - 2.21) $a_{vector\ sum}$ = 1.00 (range = 0.61 - 1.80) $a_{vector\ sum}$ = 0.83 (range = 0.42 - 1.68) $a_{vector\ sum}$ = 1.22 (range = 0.66 - 1.74) $a_{vector\ sum}$ = 0.84 (range = 0.66 - 1.07) $a_{vector\ sum}$ = 0.89 (range = 0.35 – 1.58)	NR	NR	6.2 (3.2 - 8.4)[xi] 6.7 (2.5 - 10.0) 5.4 (2.0 - 8.9) 7.1 (1.3 - 13.9) 4.4 (1.9 – 6.0) 3.2 (1.4 – 7.1)	NR	NR

[i] Not Reported

[ii] authors report "ISO risk limit", assume they mean "exposure limit"

[iii] Crest factors > 20 m/s^2 could not be measured accurately

[iv] Seat back measure

[v] From Bovenzi, 1996

[vi] $a_{gw} = (2a^2_{xw} + a^2_{yw} + a^2_{zw})^{0.5}$

[vii] While the majority of seats attenuated vibration exposure (83%), some amplified exposure (T>1).

[viii] Assume these are vector sums: $a_{vector\ sum} = (1.4\ a_{wx}^2 + 1.4\ a_{wy}^2 + a_{wz}^2)^{0.5}$

[ix] Reference values calculated as 2.5 x 10^6

[x] VDV Vibration Dose Value (BS6841); VDV should not exceed 15 m/s$^{1.75}$.

[xi] range