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

A Review of the Scientific Evidence

Report to:

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Executive Summary

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

The review was completed in three steps. We searched the scientific literature using electronic databases (Medline, EMBASE, 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, O H., 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; Thorbjornsson 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; Thorbjomsson 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-Sørensen et al., 1989; Hrubec and Nashold, 1975; Reinsbord and Greenland, 1985; Ryden et al., 1989]; gender (no consistent relationship to one sex or the other) [Lindal and Stefansson, 1996; Magora, 1970; Reinsbord and Greenland, 1985; Roncarati and McMullen, 1988]; fatigue [Svensson and Andersson, 1989; Troup and Videman, 1989]; coffee consumption [Roncarati and McMullen, 1988]; and rural residence [Hrubec and Nashold, 1975].

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

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

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

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

- **Confounders**: As described in the previous section, these are the factors, other than whole body vibration, that are related to back disorders. They have the potential to distort a study’s findings if they are also related to driving or vibration exposure. Some studies, especially the early cross-
sectional studies controlled for no or few confounders. Many of the more recent studies were able to control for a wide range of potential confounding factors.

It is not necessarily appropriate to control for every known risk factor. For example, although prior back pain is a strong predictor of new episodes, controlling for this risk factor may obscure real associations, if the occupational factor of interest led to the initial disease.

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

- **Outcome Measurements**: In most studies the disease outcome was self-reported back pain, lumbago, sciatica, or back trouble. These are subjective measures, but given that pain reporting is the basis for diagnosis, it is likely to be reliable. The questions used to elicit pain reports, and the case definitions, differed from study to study, so it would not be reasonable to compare incidence or prevalence percentages across studies, but comparisons within studies are appropriate. A number of studies used more objective measures of back disease, including herniated lumbar or cervical intervertebral discs, deviations of the lumbar spine, sickness absence or disability due to back disorders, and hospitalization records.

  A number of studies reported only the proportion (in %) of subjects and controls with the disease in question. Incidence indicates the new cases in a given time period as a proportion of the population; it is a direct measure of disease “risk”. Prevalence indicates the existing cases in a given time period as a proportion of the population, and is related to both the incidence and duration of the disease. These simple proportions were rarely controlled for confounding.

  Most studies used a ratio of disease incidence or prevalence in subjects versus controls as the measure of association between the exposure and the outcome, e.g., incidence density ratios, odds ratios, standardized hospitalization ratios, prevalence ratios. We called these ratios “relative risks” (RRs) in Table 1. A RR of 1 indicates that the disease rate is the same in subjects and controls; a RR greater than 1 indicates a higher disease rate in exposed subjects than in controls.

  RR calculations usually give an opportunity to control for confounding.

  Most of the studies included statistical tests to determine whether the results might be due to chance. These tests were sometimes reported as “p-values”; when these are less than 0.05, the result is considered statistically significant. Confidence intervals around a RR are another method of statistical testing. If a confidence interval does not include “1”, the RR is considered statistically significant.

  Based on the design characteristics described above, the studies were assigned a ranking from (A), well designed studies, to (C), studies with a number of deficiencies, considered useful mainly as contributors to the overall evidence. These rankings appear in the Author (year) column of Table 1.

  The evaluation of the evidence from the epidemiological studies appears below, based on Hill’s [1965] criteria.
3.2.1 Consistency

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

Four studies found some risks which were not elevated. In the cohort study of Bongers et al. [1988a], the risk of a sickness absence of greater than 28 days or disability pension due to all back disorders was only slightly elevated in all crane operators, and not elevated in crane operators with at least 5 years of work experience, however the risks of herniated lumbar disc and discopathy were elevated for both of these work categories. The cross-sectional study by Walsh et al. [1989] found no elevated risks for back pain in women driving more than 4 hours per day, but did for men. This study also found no elevation in lumbar 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 Juul, 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; Riihimäki et al., 1994, Jensen et al., 1996; Thorbjörnsson et al., 1998].

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

3.2.5 Plausibility

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

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

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

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

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

3.3.1 Measuring Vibration

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

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

3.3.2 Vibration Standards

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

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

The ISO provides three exposure standards:

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

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

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

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

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 internal controls showed increasing risks with increasing vibration dose.

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


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


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


Derriennic F, Touranchet B, et al. (1994) Low back pain as a function of age, exposures to ergonomic hazards, and the perception of demands in the working environment. IEA '94 6(2):180-181


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

<table>
<thead>
<tr>
<th>Study Characteristics</th>
<th>Exposure Measurements</th>
<th>Outcome Measurements - Relative Risk (95% CI), except where otherwise noted</th>
<th>Conclusions</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Study Design</strong></td>
<td><strong>Job Description</strong></td>
<td><strong>Back Pain or Back Trouble</strong></td>
<td><strong>Sciatica</strong></td>
<td><strong>lumbar</strong></td>
</tr>
<tr>
<td>Kelsey, J., and R. Hardy (1975).</td>
<td>Male Horse Vehicle Drivers (at least 50% time in car)</td>
<td>217 Hospital Controls, age and sex matched</td>
<td>Male Truck Drivers</td>
<td>Car Drivers, Both Sexes</td>
</tr>
<tr>
<td><strong>Study Design</strong></td>
<td><strong>Control</strong> Group</td>
<td><strong>Case</strong> Group</td>
<td><strong>Table 1: Epidemiological Studies of Back Pain and Injuries in Vehicle Operators</strong></td>
<td></td>
</tr>
<tr>
<td>Frymoyer, J., et al. (1980).</td>
<td>Male Horse Vehicle Drivers (at least 50% time in car)</td>
<td>217 Hospital Controls, age and sex matched</td>
<td>Male Truck Drivers</td>
<td>Car Drivers, Both Sexes</td>
</tr>
<tr>
<td>Petrovic, L. and Milosevic, M. (1985).</td>
<td>Male Horse Vehicle Drivers (at least 50% time in car)</td>
<td>217 Hospital Controls, age and sex matched</td>
<td>Male Truck Drivers</td>
<td>Car Drivers, Both Sexes</td>
</tr>
<tr>
<td>Froom, P., et al. (1984).</td>
<td>Male Horse Vehicle Drivers (at least 50% time in car)</td>
<td>217 Hospital Controls, age and sex matched</td>
<td>Male Truck Drivers</td>
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</tr>
<tr>
<td>Petrovic, L. and Milosevic, M. (1985).</td>
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<td>217 Hospital Controls, age and sex matched</td>
<td>Male Truck Drivers</td>
<td>Car Drivers, Both Sexes</td>
</tr>
<tr>
<td>Pettit, T., and F. Biing- Sommer (1987).</td>
<td>Male Horse Vehicle Drivers (at least 50% time in car)</td>
<td>217 Hospital Controls, age and sex matched</td>
<td>Male Truck Drivers</td>
<td>Car Drivers, Both Sexes</td>
</tr>
<tr>
<td>Dupuis, H. and G. Zariffi (1987).</td>
<td>Male Horse Vehicle Drivers (at least 50% time in car)</td>
<td>217 Hospital Controls, age and sex matched</td>
<td>Male Truck Drivers</td>
<td>Car Drivers, Both Sexes</td>
</tr>
</tbody>
</table>

**Author year**


**Control Groups**

- Male Horse Vehicle Drivers (at least 50% time in car).
- Male Truck Drivers.
- Car Drivers, Both Sexes.

**Confounders**

- Age, Sex, and similar race and social class.
- Age and sex matched, similar race and social class.
- Age, Daily Hours Driving, Forklifts Driven, Working Men, Unskilled Labours, Years Driving Forklift (vs. < 3 years).
- Age, Self-reported prevalence of disorders of the spine = 70% vs 54% in controls.

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

<table>
<thead>
<tr>
<th>Subject Group</th>
<th>Exposed to Vibration</th>
<th>Age</th>
<th>Back Pain or Back Trouble</th>
<th>Sciatica</th>
<th>lumbar intervertebral</th>
</tr>
</thead>
<tbody>
<tr>
<td>217 Hospital Controls</td>
<td>Male and Female Horse Vehicle Drivers</td>
<td>217</td>
<td>2.75 (p&lt;0.02)</td>
<td>4.67 (p&lt;0.02)</td>
<td>2.16 (p&lt;0.01)</td>
</tr>
<tr>
<td>500 Cadets</td>
<td>Male and Female Horse Vehicle Drivers</td>
<td>500</td>
<td>3.08 (p&lt;0.02)</td>
<td>2.2 (NS)</td>
<td>1.7 (p&lt;0.02)</td>
</tr>
<tr>
<td>64 Truck Drivers</td>
<td>Male and Female Horse Vehicle Drivers</td>
<td>64</td>
<td>2.2 (NS)</td>
<td>0</td>
<td>1.7 (p&lt;0.02)</td>
</tr>
<tr>
<td>499 Working</td>
<td>Male and Female Horse Vehicle Drivers</td>
<td>499</td>
<td>29.40%</td>
<td>10.90%</td>
<td>1.6 (NS)</td>
</tr>
<tr>
<td>240 Male Forklift</td>
<td>Male and Female Horse Vehicle Drivers</td>
<td>240</td>
<td>11%</td>
<td>63%</td>
<td>1.6 (NS)</td>
</tr>
<tr>
<td>315 Operators</td>
<td>Male and Female Horse Vehicle Drivers</td>
<td>315</td>
<td>70%</td>
<td>91%</td>
<td>13.6%</td>
</tr>
<tr>
<td>1300 Earth Moving Machines</td>
<td>Male and Female Horse Vehicle Drivers</td>
<td>1300</td>
<td>70%</td>
<td>91%</td>
<td>13.6%</td>
</tr>
</tbody>
</table>
### Study Characteristics

<table>
<thead>
<tr>
<th>Study Design</th>
<th>Subject Group</th>
<th>Control Group</th>
<th>Confounders Controlled For</th>
<th>Employment Job Description</th>
<th>Exposure Measurements</th>
<th>Outcome Measurements - Relative Risk (95% CI), except where otherwise noted</th>
<th>Conclusion(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohort Study</td>
<td>Male Floor Work in Steel Company, with similar social class</td>
<td>All Crane Operators</td>
<td>≥ 5 years of work as a Crane Operator</td>
<td>Crane operators</td>
<td>Disearly due to Displacement of Intervertebral Disc: 0.32* (90% CI) (NS)</td>
<td>The relative risk for total disability due to back disorders was 2.6. There was a 1.5-fold increase in risk of disability due to intervertebral disc herniation for each 10 years of additional exposure. Vibration acceleration levels ranging from 0.20-1.00 m/s² were considered at least partly responsible for serious back disorders. Disability due to herniated lumbar disc occurred in 4.0% (90% CI) of all workers in this study.</td>
<td>Good study, well done, some problems with loss to follow up, some of the statistics aren't clear.</td>
</tr>
<tr>
<td>Retrospective Cohort Study</td>
<td>Male Floor Workers in Steel Company with similar social class</td>
<td>Crane Operators</td>
<td>Same study as above, different</td>
<td>Crane operators</td>
<td>Disability due to Displacement of Intervertebral Disc: 0.32* (NS) (NS)</td>
<td>The relative risk for total disability due to back disorders was 2.6. There was a 1.5-fold increase in risk of disability due to intervertebral disc herniation for each 10 years of additional exposure. Vibration acceleration levels ranging from 0.20-1.00 m/s² were considered at least partly responsible for serious back disorders. Disability due to herniated lumbar disc occurred in 4.0% (90% CI) of all workers in this study.</td>
<td>Good study, well done, some problems with loss to follow up, some of the statistics aren't clear.</td>
</tr>
</tbody>
</table>

### Table 1 - 2

<table>
<thead>
<tr>
<th>Study Design</th>
<th>Subject Group</th>
<th>Control Group</th>
<th>Confounders Controlled For</th>
<th>Employment Job Description</th>
<th>Exposure Measurements</th>
<th>Outcome Measurements - Relative Risk (95% CI), except where otherwise noted</th>
<th>Conclusion(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Sectional</td>
<td>Male Bus Drivers</td>
<td>Swedish Workers</td>
<td>-</td>
<td>Bus Drivers</td>
<td>-</td>
<td>Relative risk of hospitalization (males only)</td>
<td>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 etiologically important for herniated discs. Women appeared to have a different distribution of occupations; driving among women was not reported.</td>
</tr>
<tr>
<td>Cross Sectional</td>
<td>Swedish People with back pain</td>
<td>Swedish People without back pain</td>
<td>-</td>
<td>Exposure to shaking or vibration at work</td>
<td>Prevalence in Males with back pain = 9% vs. 4% in those without (NS)</td>
<td>-</td>
<td>Good study, no vibration measures though</td>
</tr>
<tr>
<td>Cross Sectional</td>
<td>Swedish People with back pain</td>
<td>Swedish People without back pain</td>
<td>-</td>
<td>Exposure to shaking or vibration at work</td>
<td>Prevalence in Males with back pain = 9% vs. 4% in those without (NS)</td>
<td>-</td>
<td>Good study, no vibration measures though</td>
</tr>
</tbody>
</table>

### Conclusions

1. 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 etiologically important for herniated discs. Women appeared to have a different distribution of occupations; driving among women was not reported.

2. 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 etiologically important for herniated discs. Women appeared to have a different distribution of occupations; driving among women was not reported.

3. Measles may lead to the development of musculoskeletal and other health problems, and the presence of these problems may affect the overall health of individuals. In addition, there is evidence that measles can cause serious long-term effects, including hearing loss, seizures, and mental retardation. The study found that the relative risk for total disability due to back disorders was 2.6. There was a 1.5-fold increase in risk of disability due to intervertebral disc herniation for each 10 years of additional exposure. Vibration acceleration levels ranging from 0.20-1.00 m/s² were considered at least partly responsible for serious back disorders. Disability due to herniated lumbar disc occurred in 4.0% (90% CI) of all workers in this study. | Good study, well done, some problems with loss to follow up, some of the statistics aren't clear. |
<table>
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<tr>
<th>Study Characteristics</th>
<th>Exposure Measurements</th>
<th>Outcome Measurements - Relative Risk (95% CI), except where otherwise noted</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Study Design</strong></td>
<td><strong>Subject Group</strong></td>
<td><strong>Control Group</strong></td>
<td><strong>Job Description</strong></td>
</tr>
<tr>
<td>Walth, K.</td>
<td>435 Randomly Selected Residents of Whitechurch</td>
<td>Municipal Office Workers</td>
<td>Walking or Standing for more than 2 h/d, Sitting for &gt;25 h/d, Driving a Car &gt; 4 h/d, Driving a Truck, Tractor or Digger, Lifting or Moving Weights of 25 kg or more, Using Vibrating Machinery.</td>
</tr>
<tr>
<td>Walsh, K., et al.</td>
<td>113 Helicopter Pilots</td>
<td>P.M., et al. (1996).</td>
<td>Age, Height, Weight, Climate, Bending Forward, Twisting Posture, Feeling Tense.</td>
</tr>
<tr>
<td>Riihimaki, H.</td>
<td>Cross Sectional</td>
<td>Helicopter Pilots</td>
<td>Age, Prior Back Accidents, Twisted Postures, Annual Accident Reporting.</td>
</tr>
<tr>
<td>Bongers, et al.</td>
<td>Cross Sectional</td>
<td>Non-Flying Pilots</td>
<td>All Pilots, mean dose: 444 m²/s²</td>
</tr>
<tr>
<td>Heirarachy of Study Quality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Back Pain or Back Trouble</td>
<td>≥ 20 years</td>
<td>1.78* (NS)</td>
<td>16.8* (NS)</td>
</tr>
<tr>
<td>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.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well done, but its helicopter pilots and not drivers.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor study, slightly problematic with small n's and poor definitions.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>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.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Okay study, not a great deal of info.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Serious back disorders.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disability due to 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. Cross workers left their jobs due to the heavy workload, therefore the relative risks are considered unlikely to be overestimated.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Okay study, slightly problematic with small n's and poor definitions.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>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. Unmitting back pain showed the clearest relationships to occupational exposures. The fraction of disease attributable to car driving and heavy lifting is estimated to be 6% each. Heavy lifting had the strongest occupational association with low back pain.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>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 m²/s². Transient low back pain may develop into chronic low back pain.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 - 3
### Study Characteristics

<table>
<thead>
<tr>
<th>Study Participants</th>
<th>Job Description</th>
<th>Exposure</th>
<th>Outcome Measures - Relative Risk (95% CI), except where otherwise noted</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boshuizen, H.C., et al. (1990a)</td>
<td>Agricultural Workers</td>
<td>Internal Control Group</td>
<td>First Sick Leave &amp; Back Trouble</td>
<td>This study provides some evidence of an association between driving agricultural tractors and other vibrating vehicles and long-term sickness due to back disorders, especially disc disorders. Tractor drivers show a tendency to be disabled at a younger age than the control group. Intervertebral disc disorders seem to increase with vibration dose. Vibration together with twisted posture and prolonged sitting are considered responsible for the increased incidence of back pain observed in tractor drivers. Siting is not included in the analysis as sitting and driving were too closely combined.</td>
</tr>
<tr>
<td>Boshuizen, H.C., et al. (1990b)</td>
<td>Agricultural Workers who returned questionnaires in 1986 in Reference Group</td>
<td>Internal Control Group</td>
<td>Prevalence = 51%</td>
<td>There was an association between duration and dose of exposure to vibration and back pain. The increase in the prevalence of back pain with the number of driving years and accumulated vibration dose suggests that back pain is caused by tractor driving. Twisting of the spine and static posture may also contribute to back pain in this group. The risk did not increase with vibration intensity, possibly due to inaccuracies in measurement.</td>
</tr>
<tr>
<td>Burdorf, A. Cross and H. Sectional Zondervan (1990).</td>
<td>Concrete Operators in General Operations, and Maintenance Workers in Steel Factory</td>
<td>Sedentary</td>
<td>1-Year Prevalence vs 61% vs. 27% in controls</td>
<td>The combination of twisting and bending the body in a sedentary position, 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, and those who didn't respond were an over-representation of long absence from work. Controls were taken from the factory, and thus excluded individuals on sick leave.</td>
</tr>
<tr>
<td>Villemoes, T., et al. (2000).</td>
<td>Male Carriers operation</td>
<td>Sedentary</td>
<td>Prevalence = 25% vs. 10% in controls</td>
<td>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 symptomatic disc degeneration, vertebral osteophytosis, and facet osteoarthritis, 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.</td>
</tr>
<tr>
<td>Burdorf, A. Cross et al. (1991)</td>
<td>Concrete Workers in an Engineering Factory</td>
<td>Concrete Machine Operators (64%)</td>
<td>Exposure to Whole-body Vibration</td>
<td>Exposure to whole body vibration through the use of vibrators was significantly related to low back pain among concrete workers. Posture was also significant, but age was not.</td>
</tr>
</tbody>
</table>

### Exposure Measurements

<table>
<thead>
<tr>
<th>Study Characteristics</th>
<th>Vibration Exposure</th>
<th>Back Pain or Back Trouble</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boshuizen, H.C., et al. (1990a)</td>
<td>Age, Age, Height, Smoking, Twisting, Lifting, Mental Workload, Company</td>
<td>First Sick Leave &amp; Back Trouble</td>
</tr>
<tr>
<td>Boshuizen, H.C., et al. (1990b)</td>
<td>Age, Age, Height, Smoking, Twisting, Lifting, Mental Workload, Company</td>
<td>Prevalence = 51%</td>
</tr>
<tr>
<td>Burdorf, A. Cross et al. (1991)</td>
<td>Concrete Machine Operators (64%)</td>
<td>Exposure to Whole-body Vibration</td>
</tr>
</tbody>
</table>

### Table 1 - 4

<table>
<thead>
<tr>
<th>Study Direction</th>
<th>Year</th>
<th>Subject Group</th>
<th>Control Group</th>
<th>Confounders</th>
<th>Job Description</th>
<th>Vibration Exposure</th>
<th>Back Pain or Back Trouble</th>
<th>Other Outcomes</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boshuizen, H.C., et al. (1990a)</td>
<td>1990a</td>
<td>Agricultural Workers</td>
<td>Internal Control Group</td>
<td>Age, Age, Height, Smoking, Twisting, Lifting, Mental Workload, Company</td>
<td>First Sick Leave ≥ 28 days for All Back Disorders</td>
<td></td>
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</tr>
<tr>
<td>Boshuizen, H.C., et al. (1990b)</td>
<td>1990b</td>
<td>Agricultural Workers who returned questionnaires in 1986</td>
<td>Internal Control Group</td>
<td>Age, Age, Height, Smoking, Twisting, Lifting, Mental Workload, Company</td>
<td>Prevalence = 51%</td>
<td></td>
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</tr>
<tr>
<td>Burdorf, A. Cross et al. (1991)</td>
<td>1991</td>
<td>Concrete Workers in an Engineering Factory</td>
<td>Concrete Machine Operators (64%)</td>
<td>Exposure to Whole-body Vibration</td>
<td>Prevalence = 51%</td>
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</tbody>
</table>
### Study Characteristics

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Study Design</th>
<th>Study Group</th>
<th>Control Group</th>
<th>Confounders Controlled for</th>
<th>Job Description</th>
<th>Exposure Measurements</th>
<th>Outcome Measurements - Relative Risk (95% CI), except where otherwise noted</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kivima, M., et al. (1991).</td>
<td>Cross-Sectional</td>
<td>2,727 Men</td>
<td>2,946 Women (aged 30-64)</td>
<td>Age, Smoking, Alcohol, Mental Stress, Vibration dose, Previous Back Injury, Height, Body Mass Index, Parity, Occupational History</td>
<td>Professional Driving</td>
<td>Back Pain or Back Trouble</td>
<td>1.4 (1.0-2.0)*</td>
<td>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.</td>
</tr>
<tr>
<td>Johansson, E. (1991).</td>
<td>Cross-Sectional</td>
<td>92 Subway Train Operators</td>
<td>82 Tower Operators, with similar demographic characteristics, job histories and responsibility.</td>
<td>Age, Age, Gender, Job Title, Employment Duration.</td>
<td>Subway Train Operators</td>
<td>Prevalence = 60% Self-Report, 20% Doctor Confirmation</td>
<td>1.1 (0.7-1.6)*</td>
<td>Subway train operator had a nearly four-fold increased risk of developing sciatica. The risk of sciatica did not increase with the duration of employment. In 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.</td>
</tr>
<tr>
<td>Nayha, S., et al. (1991).</td>
<td>Cross-Sectional</td>
<td>7,075 Reindeer Herders (using motorcycles and four-wheelers)</td>
<td>Reference group (analysis by risk factor)</td>
<td>Age, Internal Reference</td>
<td>Vibration</td>
<td>ASE, Age, Height, Smoking, Alcohol, Mental Stress, Previous Back Injury, Postures, Lifting, Looking Backwards, Hours Spent Sitting.</td>
<td>Prevalence = 15% vs. 7% in controls</td>
<td>Prevalence of all back pain and sciatica increased somewhat with number of days worked per year.</td>
</tr>
<tr>
<td>Bovenzi, M. and A. Zadini (1992).</td>
<td>Cross-Sectional</td>
<td>242 Drivers of 210 Workers</td>
<td>234 Urban Bus Drivers with more than 5 years of employment (aged 26-55)</td>
<td>Age, Height, Weight, Education, Smoking, Sport Activity, Frequency of More than 5 years of employment</td>
<td>Radio Dispatchers, Dispatcher, Security Guards, Forklift Operators, and Others</td>
<td>Back Pain: Lumbago: Sciatica, 1-Year</td>
<td>2.2 (1.5-4.7)*</td>
<td>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 etiopathology of lumbar spine disorders. Low back pain and leg pain increased with age in both sexes 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.</td>
</tr>
<tr>
<td>Chernyuk, V.I. (1992).</td>
<td>Cross-Sectional</td>
<td>833 Tractors</td>
<td>Urban Reference</td>
<td>Years of employment:</td>
<td>Prevalence of Chronic Lumbago (Calculated from Chronic Lumbago)</td>
<td>The prevalence of chronic low back pain increased with years of both service as a tractor driver and exposure to vibration, particularly at higher vibration doses.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 1 - 5
Mayahira, Cross Sectional Study (1992) (C)

- **Author**: Mayahira, K., et al.
- **Year**: 1992
- **Title**: Cross Sectional Study
- **Subjects**: Power Shovel Operators, 127 Bulldozer Operators, 44 Forklift Operators
- **Ages**: (aged 30 - 49)
- **Exposure**: Vibration exposure
- **Outcome**: Low back pain or back trouble
- **Methods**: 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.

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Bovarini, M., Cross Sectional Study (1994) (A)

- **Author**: Bovarini, M., Cross Sectional Study (1994) (A)
- **Year**: 1994
- **Title**: Cross Sectional Study
- **Subjects**: Tractor Drivers, 620 Revenue Officers
- **Ages**: Age, Body Mass (BMI), Index, Education, Martial Status, Civil Status
- **Exposure**: Tractor Driving
- **Outcome**: Lifetime Prevalence = 100% vs. 34% in the controls
- **Methods**: Long-lasting 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.

---

Piette, F., et al. Cohort Study (1992) (A)

- **Author**: Piette, F., et al.
- **Year**: 1992
- **Title**: Cohort Study
- **Subjects**: Commercial Travelers (1376 Male, 343 Female)
- **Ages**: (19-25 years)
- **Exposure**: Power Shovel Operators, 95 Male Straddle Carrier Drivers
- **Outcome**: Lifetime Prevalence = 100% vs. 34% in the controls
- **Methods**: 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.

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Hatfield, A. Cross Sectional Study (1993) (C)

- **Author**: Hatfield, A.
- **Year**: 1993
- **Title**: Cross Sectional Study
- **Subjects**: Male Office Workers, 100 Male Crane Operators, 95 Male Straddle Carrier Drivers
- **Ages**: Age, Height, Weight, Occupational History, Psychological Stress, Climatic Conditions, Job Satisfaction
- **Exposure**: Vibration exposure
- **Outcome**: Lifetime Prevalence = 100% vs. 34% in the controls
- **Methods**: Long-lasting 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.
<table>
<thead>
<tr>
<th>Study Characteristics</th>
<th>Exposure Measurements</th>
<th>Outcome Measurements - Relative Risk (95% CI), except where otherwise noted</th>
<th>Conclusions</th>
<th>Hierarchy of Study Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author (year)</td>
<td>Study Design</td>
<td>Subject Group</td>
<td>Control Group</td>
<td>Confounders Controlled For</td>
</tr>
<tr>
<td>Heirarchy of Study</td>
<td>Quality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barbiers, G., et al. (1995)</td>
<td>Cohort Study</td>
<td>Male Tractor Drivers with &gt; 5 years of employment.</td>
<td>Age, Stratified</td>
<td>Senility, Smoking, Physical Exercise, Amount of Twisted Posture, High Pace of Work, Workmate Problems, Draft, Cold, Vibration, Back Accidents, Other Low Back Pain</td>
</tr>
<tr>
<td>Gui, H.-R., et al. (1985)</td>
<td>Cross Sectional Survey</td>
<td>5,256 workers: 24,816 other with back pain workers from the US National Health Interview Survey</td>
<td>Sex (stratified and weighted to structure of US population: incompletely described)</td>
<td>Male Drivers: Industrial truck and tractor equipment</td>
</tr>
<tr>
<td>Jensen, M.F. et al. (1986)</td>
<td>Cohort Study</td>
<td>89,146 Male Professional Drivers (aged 15-59) 1.3 million Employed Swedish Males (aged 15-59)</td>
<td>Age, Calendar Year</td>
<td>All Drivers</td>
</tr>
<tr>
<td>Study Characteristics</td>
<td>Exposure Measurements</td>
<td>Outcome Measurements - Relative Risk (95% CI), except where otherwise noted</td>
<td>Conclusions</td>
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<tr>
<td>Author (year)</td>
<td>Study Design</td>
<td>Subject Group</td>
<td>Control Group</td>
<td>Confounders Controlled For</td>
</tr>
<tr>
<td>Lumis, J., et al. (1996)</td>
<td>Cross Sectional</td>
<td>18,920 Ontario Residents (aged 16-64)</td>
<td>Internal Reference Group (analyzed by exceptional risk factors)</td>
<td>Age, Sex, Smoking</td>
</tr>
<tr>
<td>Magnusson, M.L., et al. (1996).</td>
<td>Cross Sectional</td>
<td>111 Male Bus Drivers, 117 Male Truck Drivers</td>
<td>Age, Height, Weight, Work Satisfaction, Stress, Living Habits, Social Status, Work Environment, Posture on the Job, Psychosocial Factors.</td>
<td>Drivers: Long-Term</td>
</tr>
<tr>
<td>Xu, Y., et al. (1997)</td>
<td>Cross Sectional</td>
<td>5,185 randomly sampled members of the Danish population who were employed in 1990 (aged 18 - 59)</td>
<td>Internal reference group (analysis by risk factor)</td>
<td>Sex, Age, Education, Duration of Employment, Occupation</td>
</tr>
<tr>
<td>Thorbjörnsson, C.O.B., et al. (1998)</td>
<td>Cross Sectional; Cohort (1998) Cohort</td>
<td>252 Women with musculo-skeletal diagnosis in a 1969 study of a population from Stockholm county.</td>
<td>Internal reference group (analysis by risk factor)</td>
<td>Age, Previous Low Back Pain</td>
</tr>
</tbody>
</table>

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

Table 1 - 8
Table 2: Levels of Exposure to Whole Body Vibration in Vehicle Operators

<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Industry; Study Conditions; Study Objectives</th>
<th>Measurement Location; Device Type; Sample Duration</th>
<th>Vehicle Types</th>
<th>Vehicle Specifics</th>
<th>Vibration Exposure Levels (Exposure in Root Mean Square m/s² unless otherwise specified)</th>
<th>Dominant Vibration Frequencies (Hz)</th>
<th>Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)</th>
<th>Peak Exposure or Crest Factors (CF, ( \frac{C_{peak}}{h_{rms}} ))</th>
<th>Jobs and shocks</th>
<th>Determinants of Vibration Exposure (other than vehicle type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heino, Ketola, Makela, Makinen, Niemela, Starck, and Partanen, 1978</td>
<td>Locomotive engineers; Mostly with loco/s running on main tracks; Exposure assessment.</td>
<td>At seat; Tri-axial accelerometers; Sample duration 0.5 – 2 hr.</td>
<td>35 locomotives of 15 different types (3 categories based on power source and cab position).</td>
<td>Electric, cab at both ends Diesel, center cab Diesel, cab at both ends</td>
<td>NR</td>
<td></td>
<td>In general, highest components of z-axis vibration were at 2 – 4 Hz.</td>
<td>72 % of measurements &gt; EL 19 % of measurements &gt; EL 24 % of measurements &gt; EL</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Howat, 1978</td>
<td>Forestry Vehicles; Dry-land sort; Exposure assessment.</td>
<td>Seat; Z-axis only; 15 minute sample.</td>
<td>Caterpillar logging vehicles.</td>
<td>Caterpillar 966 (Manuf. 1973) Caterpillar 966 (Manuf. 1977) Caterpillar 980 Caterpillar 968</td>
<td>Exceeds 1 m/s² ~95% of observations Exceeds 1 m/s² ~65% of observations Exceeds 1 m/s² ~55% of observations Exceeds 1 m/s² ~15% of observations</td>
<td>NR</td>
<td>98% obs &gt; 8hour ISO FDP 92% obs &gt; 8hour ISO FDP 92% obs &gt; 8hour ISO FDP 25-55% obs &gt; 8hour ISO FDP</td>
<td>NR</td>
<td>NR</td>
<td>Work rate</td>
</tr>
<tr>
<td>Hansson and Wikstrom, 1981</td>
<td>Forestry equipment operators; Road and off road Conditions; comparing subjective evaluation with objective measurements.</td>
<td>At seat; Tri-axial measurements; Samples &lt; 4 minutes.</td>
<td>Off-road forestry vehicles; 42 drivers.</td>
<td>5 different vehicles.</td>
<td>( h_{rms} \text{ z-axis} = 0.18 – 1.78 \text{ m/s}^2 ) ( z-axis = 1.5 – 3.0 \text{ Hz} )</td>
<td>NR</td>
<td></td>
<td>Crest factors in range 3-7</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Redmond and Remington, 1986</td>
<td>Coal Mining; Normal operating conditions; Exposure assessment study.</td>
<td>At seat; Tri-axial accelerometers; 12 - 18 minute samples.</td>
<td>Surface and underground vehicles (N=86 samples).</td>
<td></td>
<td>NR</td>
<td>NR</td>
<td>Probability (%) of exceeding ISO 2631 EL in:</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
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<td></td>
<td></td>
<td>Any axis</td>
<td>&quot;Z-Axis&quot;</td>
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<td></td>
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<td></td>
<td>Surface machines: Bull dozers</td>
<td>33.8</td>
<td>13.3</td>
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<td></td>
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<td>Scrapers</td>
<td>42.5</td>
<td>22.0</td>
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<td></td>
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<td></td>
<td>Haulers (off-highway)</td>
<td>17.6</td>
<td>14.2</td>
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<td></td>
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<td></td>
<td>Highway trucks</td>
<td>8.8</td>
<td>8.5</td>
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<td>Loaders</td>
<td>31.1</td>
<td>10.6</td>
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<td></td>
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<td>Blast hole drills</td>
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<td>Motor graders</td>
<td>01.0</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Shovels and draglines</td>
<td>0.0</td>
<td>0.0</td>
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<td></td>
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<td>Underground:</td>
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<td></td>
<td>Continuous miner</td>
<td>2.0</td>
<td>2.0</td>
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</tbody>
</table>

Table 2 - 1
<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Industry; Study Conditions; Study Objectives</th>
<th>Vehicle Types</th>
<th>Vibration Exposure Levels (Exposure in Root Mean Square m/s² unless otherwise specified)</th>
<th>Dominant Vibration Frequencies (Hz)</th>
<th>Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)</th>
<th>Peak Exposure or Crest Factors (CF, ( \text{apeak}/\text{arms} ))</th>
<th>Jobs and shocks</th>
<th>Determinants of Vibration Exposure (other than vehicle type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redmond and Remington, Cont'd</td>
<td>Personnel carrier; Haulage vehicle; Bridge conveyor</td>
<td>Crane operators; Operating conditions NR; Health Study</td>
<td>Crane Operators.</td>
<td>( a_v = 0.25 - 0.67 \text{ m/s}^2 )</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>[Bongers, Boshuizen, Hulshof and Koemeester, 1988a]</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
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<tr>
<td>[Netterstrom and Juel, 1989]</td>
<td>Bus drivers; Operating conditions NR; Health Study</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>[Village, Morrison and Leong, 1989]</td>
<td>At seat; Tri-axial accelerometers; Sampled over set of standard tasks.</td>
<td>Load-haul-dump vehicles (N=22 samples).</td>
<td>8 yd capacity 6 yd capacity 5 yd capacity 3.5 yd capacity</td>
<td>( a_x = 0.5 - 1.0; a_y = 0.6 - 0.7; a_z = 0.7 - 1.4 ) ( a_x = 0.4 - 1.4; a_y = 0.5 - 0.6; a_z = 0.6 - 1.6 ) ( a_x = 0.6 - 0.8; a_y = 0.6 - 0.8; a_z = 0.8 - 1.2 ) ( a_x = 0.5 - 1.5; a_y = 0.6 - 0.7; a_z = 0.8 - 2.5 )</td>
<td>( x,y: 1.6 - 2.0 ) ( z = 3.15 \text{ Hz} )</td>
<td>20/22 sets of measurements exceed ISO 2631; 90% of vehicles exceeded ( \text{EL}_x ) and ( \text{EL}_z ); 52% exceeded ( \text{EL}_y ). Using ISO task-based scheme, all samples &gt; EL.</td>
<td>Peaks range from 1.2 to 20 m/s², but no consistent pattern. 76% (mine A), 43% of samples (mine B) exceeded crest factor of 6.</td>
<td>Drivers exposed to random jolts of &gt; 20 m/s², well in excess of ISO 2631. Operators leave seat, creating additional impact forces.</td>
</tr>
<tr>
<td>[Boshuizen, Hulshof and Bongers, 1990]</td>
<td>Agricultural vehicles; Normal working conditions; Health Study.</td>
<td>Measurement location NR; Triaxial accelerometer; Sample duration NR.</td>
<td>Tractors, bulldozers, combine harvesters, lorry, van and car.</td>
<td>Tractor in field (n=4) Heavy tractor in field Tractor on asphalt road (n=4) Tractor and trailer on asphalt Tractor on brick road (n=3) Bulldozer, standard seat (n=3) Bulldozer, anti-vibrat'n seat (n=4) Combine harvester Lorry Van Car</td>
<td>( a_{\text{vector sum}} = 0.50 - 0.59 ) ( a_{\text{vector sum}} = 1.47 ) ( a_{\text{vector sum}} = 0.67 - 0.98 ) ( a_{\text{vector sum}} = 1.17 ) ( a_{\text{vector sum}} = 1.76 - 2.03 ) ( a_{\text{vector sum}} = 0.52 - 0.64 ) ( a_{\text{vector sum}} = 0.43 - 0.80 ) ( a_{\text{vector sum}} = 0.28 ) ( a_{\text{vector sum}} = 0.78 ) ( a_{\text{vector sum}} = 0.37 )</td>
<td>( a_{\text{vector sum}} = 0.25 )</td>
<td></td>
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</tr>
<tr>
<td>Author (year)</td>
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<td>Dominant Vibration Frequencies (Hz)</td>
<td>Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)</td>
<td>Peak Exposure or Crest Factors (CF, apeak/awave)</td>
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</tr>
<tr>
<td>[Bongers, Hulshof, et al, 1990]</td>
<td>Helicopter pilots; Representative flight conditions; Health study.</td>
<td>Measurement location NR; Triaxial accelerometer; Sample duration NR.</td>
<td>4 Helicopter types, two vehicles of each type measured.</td>
<td>Alouette III</td>
<td>a_x = 0.12-0.17, a_y = 0.17-0.25, a_z = 0.44-0.67</td>
<td>x, y, z = 16</td>
<td>FDP reached at 2-4 hrs at a_z</td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bolkow 105</td>
<td>a_x = 0.09-0.13, a_y = 0.13-0.18, a_z = 0.29-0.49</td>
<td>x, z = 25, y = 6</td>
<td>FDP reached at 3-7 hrs at a_z</td>
<td>x, y = 16, z=8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sikorsky 61</td>
<td>a_x = 0.06-0.11, a_y = 0.10-0.21, a_z = 0.17-0.44</td>
<td>x, y = 16, z=8</td>
<td>FDP reached at 4-13 hrs at a_z</td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>Sikorsky 76</td>
<td>a_x = 0.24-0.55, a_y = 0.07-0.14, a_z = 0.17-0.36</td>
<td>x, y = 20, z=8</td>
<td>FDP reached at 5-10 hrs at a_z</td>
<td></td>
</tr>
<tr>
<td>[Griffen, 1990]</td>
<td>Road and agricultural vehicles; Normal operating conditions; Exposure assessment.</td>
<td>Seat; Triaxial accelerometer; 15-30 minute samples.</td>
<td>Various road and agricultural vehicles.</td>
<td>Autos, and Vans (n=11)</td>
<td>a_x = 0.25 – 1.00</td>
<td></td>
<td></td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bus (n=3)</td>
<td>a_x = 0.40 – 1.75</td>
<td></td>
<td></td>
<td>NR</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Auto (city road)</td>
<td>a_x = 0.60 – 1.30</td>
<td></td>
<td></td>
<td>NR</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Van Country road</td>
<td>a_x = 0.43</td>
<td></td>
<td></td>
<td>NR</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Truck Rough road</td>
<td>a_x = 0.89</td>
<td></td>
<td></td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tractors, mowing</td>
<td>a_x = 1.06</td>
<td></td>
<td></td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tractors, hay turning</td>
<td>a_x = 1.20</td>
<td></td>
<td></td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tractors, farm road</td>
<td>a_x = 2.00</td>
<td></td>
<td></td>
<td>NR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Road surface</td>
<td>a_x = 2.24</td>
<td></td>
<td></td>
<td>NR</td>
</tr>
<tr>
<td>[Johanning, Wilder, Landrigan, and Pope, 1991]</td>
<td>Subway trains; Normal operating conditions; Exposure assessment.</td>
<td>At seat; Tri-axial accelerometer; 2 hrs of data.</td>
<td>Old (1948) to new (1988) subway cars.</td>
<td>Mean of all car types: a_x = 0.25 – 1.00, a_y = 0.40 – 1.75, a_z = 0.60 – 1.30</td>
<td>a_x = 0.55 (range 0.32 – 0.99)</td>
<td></td>
<td></td>
<td>NR</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Specific car types:</td>
<td>a_x = 0.10, a_y = 0.26, a_z = 0.37</td>
<td></td>
<td></td>
<td>NR</td>
</tr>
<tr>
<td>[Boshuizen, Bongers, Hulshof, 1992]</td>
<td>Heavy Equipment; Normal working conditions; Health study.</td>
<td>At seat; Tri-axial accelerometer; Sample duration approx. 5 min.</td>
<td>2 forklifts and freight tractor.</td>
<td>a_x = 0.10, a_y = 0.21, a_z = 0.33</td>
<td>a_max = 0.80 m/s²</td>
<td></td>
<td></td>
<td>NR</td>
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<td></td>
<td></td>
<td>a_x = 0.08; a_y = 0.19; a_z = 0.29</td>
<td>a_max = 0.79 m/s²</td>
<td></td>
<td></td>
<td>NR</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Small forklift</td>
<td>a_x = 0.80 m/s²</td>
<td>3.15 Hz</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td>Large forklift</td>
<td>a_x = 0.79 m/s²</td>
<td>2.5 Hz</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Freight container tractor</td>
<td>a_x = 1.04 m/s²</td>
<td>1.6, 2.5 Hz</td>
<td></td>
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</tr>
</tbody>
</table>

Table 2 - 3
<table>
<thead>
<tr>
<th>Author (year)</th>
<th>Industry; Study Conditions; Study Objectives</th>
<th>Measurement Location; Device Type; Sample Duration</th>
<th>Vehicle Types</th>
<th>Vehicle Specifics</th>
<th>Vibration Exposure Levels</th>
<th>Dominant Vibration Frequencies (Hz)</th>
<th>Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)</th>
<th>Peak Exposure or Crest Factors (CF, $a_{peak}/a_{rms}$)</th>
<th>Jobs and shocks</th>
<th>Determinants of Vibration Exposure (other than vehicle type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Bovenzi and Zadini, 1992]</td>
<td>Bus Drivers; Actual driving conditions; Health study.</td>
<td>Seat; Triaxial accelerometer; 15-30 minute samples.</td>
<td>Older Fiat buses (manuf. 1968-1973), Newer Inveco and Inbus buses (manuf. 1987-1990).</td>
<td>Fiat 409 DSU</td>
<td>$a_{xyz} = 0.12$, $a_{xyz} = 0.16$, $a_{xyz} = 0.65$, $a_{xyz} = 0.15$</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>Authors comment that seat suspension in old Fiat buses (transmissibility, $T = a_{zw,seat}/a_{zw,floor}$) varied from 1.6 to 1.9, while in newer Inbus and Inveco buses $T = 1.1$ to 1.25.</td>
</tr>
<tr>
<td>[Piette and Malchaire, 1992]</td>
<td>Steel works; Normal operating conditions; Determinants of exposure analysis.</td>
<td>At seat and floor; Tri-axial accelerometers; 2 minute samples.</td>
<td>70 Cranes.</td>
<td>Mid-span cab Eind cab</td>
<td>$a_{xyz} = 0.37 – 1.14$</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>Peaks found at 4 - 8 Hz 621 cranes in excess of FDP; none above EL.</td>
</tr>
<tr>
<td>[Burdorf, Naaktgebore, and de Groot 1993]</td>
<td>Port workers; Variety of working conditions; Health study.</td>
<td>Measurement location NR; Tri-axial accelerometers; 5 min samples.</td>
<td>20 Cranes, 21 straddle carriers.</td>
<td>Cranes Straddle carriers</td>
<td>$a_{xyz} = 0.15$, $a_{xyz} = 0.11$, $a_{xyz} = 0.17$</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>Crane span, load, runway condition, cabin position, suspension, seat, speed.</td>
</tr>
<tr>
<td>[Burdorf and Swuste, 1993]</td>
<td>Professional Drivers; Normal working conditions; Study of attenuation efficiency of suspension seats.</td>
<td>Seat and Floor; Tri-axial accelerometer but study limited to $a_{zw}$ sample duration 5 min.</td>
<td>Lorries Fork lifts Tractors.</td>
<td>Lorries Fork lifts Tractors</td>
<td>$a_{xyz} = 0.50 – 0.99$</td>
<td>1.15 – 2.7 Hz</td>
<td>All worksite measurements exceeded 8hr ISO 2631 FDP level, and 9/24 worksites exceeded EL.</td>
<td>NR</td>
<td>NR</td>
<td>Seat suspension characteristics: Mean Seat transmissibility ($T = a_{zw,seat}/a_{zw,floor}$) varies from 0.34 – 1.3.</td>
</tr>
<tr>
<td>[Anttonen and Niskanen, 1994]</td>
<td>Reindeer herding; Typical working conditions; Exposure assessment.</td>
<td>At seat and foot board; Tri-axial accelerometers; Sample duration 10 – 50 minutes.</td>
<td>Snowmobiles: Old (1974) to New (1993) designs.</td>
<td>Snowmobiles: Old (1974) to New (1993) designs.</td>
<td>$a_{xyz} = 1.1$</td>
<td>2.6 Hz 4.40 Hz 2.0 Hz 10.63 Hz 2 Hz 8 Hz</td>
<td>Majority of measurements exceeded proposed European standards (0.7 m/s², ceiling value).</td>
<td>NR</td>
<td>NR</td>
<td>Shocks considered high risk for snowmobilers. Seat resonance (i.e. amplifying rather than attenuating frame vibration), uneven terrain, speed.</td>
</tr>
<tr>
<td>Author (year)</td>
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<td>Vehicle Types</td>
<td>Vehicle Specifics</td>
<td>Vibration Exposure Levels (Exposure in Root Mean Square m/s² unless otherwise specified)</td>
<td>Dominant Vibration Frequencies (Hz)</td>
<td>Compliance with ISO 2631 (EL = Exposure Level, FDP = Fatigue Decreased Proficiency Level)</td>
<td>Peak Exposure or Crest Factors (CF, $a_{peak}/a_{rms}$)</td>
<td>Jobs and shocks</td>
<td>Determinants of Vibration Exposure (other than vehicle type)</td>
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<tr>
<td>[Bovenzi and Betta, 1994]</td>
<td>Tractors; Normal operating conditions; Health study.</td>
<td>At seat; Tri-axial accelerometer; Sampling duration NR.</td>
<td>Low-power tractors (45-85 hp).</td>
<td>Fiat (50-70 hp) $n = 14$ Ford (45-60 hp) $n=23$</td>
<td>$a_{peak}$-mean = 1.24 (mean, range = 0.58-2.00) $a_{rms}$-mean = 0.96 (mean, range = 0.36-2.03) $a_{peak}$-mean = 0.89 (mean, range = 0.53-1.25)</td>
<td>2.5 - 4 Hz</td>
<td>For estimated daily average exposure (2.7 hours), mean value of frequency weighted acceleration is below EL.</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>[Ozkaya, Willems and Goldsheyder, 1994]</td>
<td>Subway trains; Normal operating conditions; Exposure assessment.</td>
<td>At seat; Tri-axial accelerometer; 48 round trips giving 100 hours of data.</td>
<td>Subway car.</td>
<td>16 different types</td>
<td>Average acceleration (by subway line) ranging from 0.37 m/s² to 0.57 m/s²</td>
<td>NR</td>
<td>Exposure levels above ISO 2631 FDP 6/20 lines; none over EL.</td>
<td>NR</td>
<td>NR</td>
<td>Speed, track type and condition, car type, maintenance, passenger load, driver experience.</td>
</tr>
<tr>
<td>[Barbieri, Mattoli, Grillo, Geminni, Mancini and Raffi, 1995]</td>
<td>Tractors; Operating conditions NR; Health study.</td>
<td>Measurement location NR; Device type NR; Summary data of 10,000+ obs.</td>
<td>Agricultural tractors.</td>
<td>50% of tractors acceleration between 1.16 m/s² and 1.93 m/s²</td>
<td>$z = 4.5$</td>
<td>FDP exceeded in between 21 and 58 minutes at 1.16 m/s² and 1.93 m/s² respectively.</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>[Suvorov, Staroezhuk, Tsentina, and Lagutina, 1996]</td>
<td>Heavy equipment; Conditions NR; Exposure assessment.</td>
<td>Heavy equipment – 90 different vehicle types.</td>
<td>Tractor Bulldozers</td>
<td>69 dB</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>[Ozkaya, Goldsheyder and Willems, 1997]</td>
<td>Subway trains; Normal operating conditions; Exposure assessment.</td>
<td>At seat; Tri-axial accelerometer; Sample duration between 43 and 660 sec.</td>
<td>2 new-technology subway trains.</td>
<td>“A-line”, new car “A-line”, old car “2-line”, new car “2-line”, old car</td>
<td>$a_{peak}$ = 0.18; $a_{rms}$-mean = 0.38 $a_{peak}$ = 0.27 – 0.34; $a_{rms}$-mean = 0.51 – 0.53 $a_{peak}$ = 0.12; $a_{rms}$-mean = 0.26 $a_{peak}$ = 0.20; $a_{rms}$-mean = 0.38</td>
<td>NR</td>
<td>Older cars both exceed FDP boundary; new car only 23% of FDP boundary.</td>
<td>NR</td>
<td>NR</td>
<td>Suspension, air better than springs.</td>
</tr>
<tr>
<td>[Robinson, Martin, Rodkan, Gibbs, and Duttall, 1997]</td>
<td>Mining; Typical operating conditions; Exposure assessment for return to work planning.</td>
<td>At seat; Tri-axial measurements; Sampling duration NR.</td>
<td>Representative sample of mine equipment.</td>
<td>Heavy Trucks Light Trucks Earth Movers</td>
<td>$a_{peak}$ = 0.7 – 1.0 $a_{rms}$ = 1.0 – 2.0 $a_{rms}$ = 0.7 – 1.0</td>
<td>All vehicles &gt; ISO 2631 FDP8hr. Range of Vibration Dose Value (VDV) $x = 13 – 33$ m/s¹.⁷</td>
<td>$CF_z = 7.8 – 18.8$ $CF_z = 7.4 – 17.5$ $CF_z = 10.6 – 24.0$</td>
<td>Total of 8 of 11 vehicles CF &gt; 10</td>
<td>Vehicle and roadway maintenance.</td>
<td></td>
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</tbody>
</table>

Table 2 - 5
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<thead>
<tr>
<th>Author (year)</th>
<th>Industry; Study Conditions; Study Objectives</th>
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<th>Vehicle Types</th>
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<th>Jobs and shocks Determinants of Vibration Exposure (other than vehicle type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Futatsuka, Maeda, Inaoka, Nagano, Shono, and Miyakita, 1998]</td>
<td>Agricultural equipment; Normal working conditions; Exposure assessment.</td>
<td>At seat; Tri-axial measurements; Each vehicle tested on 4 runs, each of 30 sec duration.</td>
<td>Combine (Iseki HL7000) Combine (Iseki 197) Combine (Yanmar TC 2200M) Tractor (Kubota MI 46) Hinomoto (NX 23) Riding rice power Transplanter Farm Carrier Cultivator Tea leaf plucker</td>
<td>Combine (Iseki HL7000) Combine (Iseki 197) Combine (Yanmar TC 2200M) Tractor (Kubota MI 46) Hinomoto (NX 23) Riding rice power Transplanter Farm Carrier Cultivator Tea leaf plucker</td>
<td>$a_{rms} = 0.41$ $a_{rms} = 0.57$ $a_{rms} = 1.03$ $a_{rms} = 0.89$ $a_{rms} = 0.43$ $a_{rms} = 0.35$ $a_{rms} = 0.59$ $a_{rms} = 1.00$ $a_{rms} = 0.54$ $a_{rms} = 1.63$</td>
<td>NR</td>
<td>All vehicle above FDP 8-hour limit. Four vehicles (Yanmar combine, Kubota tractor, Yanmar carrier and the tea-picker) were above the 8-hour EL.</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>[Holmlund and Lundstrom, 1999]</td>
<td>Heavy Equipment; Normal working conditions; exposure assessment.</td>
<td>NR</td>
<td>Several heavy equipment types (N=57).</td>
<td>Band Excavator (e.g. D5 Cat) Dumpor (e.g. Volvo DR 860) Excavator (e.g. Cat 225 LC) Loader (e.g. Cat 225 LC) Grader (e.g. Cat 140) Tractor Excavator (e.g. Ford 550)</td>
<td>$a_{rms} = 1.84$ (range = 1.50 - 2.21) $a_{rms} = 1.00$ (range = 0.61 - 1.80) $a_{rms} = 0.83$ (range = 0.42 - 1.68) $a_{rms} = 1.22$ (range = 0.66 - 1.74) $a_{rms} = 0.84$ (range = 0.66 - 1.07) $a_{rms} = 0.89$ (range = 0.35 – 1.58)</td>
<td>NR</td>
<td>NR</td>
<td>6.2 (3.2 - 8.4) NR</td>
<td>NR</td>
</tr>
</tbody>
</table>

1. Not Reported
2. Authors report "ISO risk limit", assume they mean "exposure limit"
3. Crest factors > 20 m/s² could not be measured accurately
4. Seat back measure
5. From Bovenzi, 1996
6. $a_{rms} = (2a_{w1}^2 + a_{w2}^2 + a_{wz}^2)^{0.5}$
7. While the majority of seats attenuated vibration exposure (83%), some amplified exposure ($T>1$).
8. Assume these are vector sums: $a_{rms} = (1.4 a_{wx}^2 + 1.4 a_{wy}^2 + a_{wz}^2)^{0.5}$
9. Reference values calculated as $2.5 \times 10^6$
10. VDV Vibration Dose Value (BS6841); VDV should not exceed 15 m/s$^{1.75}$
11. range