



**Department of Transport and Regional Services
Australian Transport Safety Bureau**

Heavy Vehicle Seat Vibration and Driver Fatigue

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ARRB Transport Research Ltd

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Heavy Vehicle Seat Vibration and Driver Fatigue

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Abstract

In studies and in anecdotal evidence a relationship between vibration in heavy vehicles and driver fatigue has been assumed, without supporting evidence. A literature review identified a few studies showing a possible association between fatigue and low frequency vibration that is typical of the vibration frequencies experienced by heavy vehicle drivers. An experimental study would be needed to determine whether the effect of vibration would be noticeable among known contributors to fatigue (eg, time awake, time on task, rest and sleep, circadian factors).

Research has also associated whole body vibration exposure with adverse health effects on the human body. Limited available data suggests that exposure to vibration of Australian heavy vehicle drivers may be high, putting drivers at risk to health. A field study of vibration levels experienced by Australian truck drivers would be necessary to determine actual vibration exposure levels and establish standards for trucks sold in Australia.

Keywords

SAFETY/ HEAVY VEHICLES/ DRIVER FATIGUE/ VIBRATION/ DRIVER HEALTH/ OH&S

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Executive Summary

In many studies a relationship between vibration and fatigue has been assumed without supporting research, and often based only on anecdotal evidence. The study of fatigue as it relates to vibration is complex and there is limited research available. However, the literature review has identified a few studies showing a possible association between fatigue and low frequency vibration that is typical of the vibration frequencies experienced by truck drivers. These findings could form the basis of further research in this area.

Past research has associated whole-body vibration exposure with a number of adverse effects on the human body. The effects of vibration on the lower back and spine have been extensively researched and documented. Effects on the gastrointestinal system have received less attention but are considered by some to be significant.

The following points summarise the findings of the literature review:

- There is some laboratory and field research that supports a relationship between low frequency vibration (3 Hz) and increased fatigue or drowsiness. This may have implications for heavy vehicle truck drivers who usually experience vibration levels around this frequency while driving.
- Intermittent and random vibration can have a stimulating or wakening effect.
- Vibration exposure has been found to cause changes to body metabolism and chemistry that could lead to fatigue effects.
- The health effects of whole-body vibration have been extensively researched and adverse effects have been established. Truck drivers shown many of the symptoms of adverse health effects associated with whole-body vibration exposure.
- Typical whole-body vibration exposure levels of heavy vehicle drivers are in the range 0.4 – 2.0 m/s² with a mean value of 0.7 m/s² in the vertical (z-axis). Vertical vibration is highest in the frequency range 2 – 4 Hz.
- The average whole-body vibration level experienced by drivers of heavy transport vehicles exceed health, fatigue and comfort limits of the Australian Standard and most exposures are within the Caution zone (for health) according to the current International Standard. Many typical exposures will reach the likely health risk zone of the International Standard. According to these standards, many truck drivers are at risk of incurring adverse health effects from prolonged exposure to vibration.
- There is evidence that truck drivers have back complaints that could be partly attributable to whole-body vibration exposure.
- Comfort limits of both Australian and International Standards are exceeded by most vehicle rides.

Exposure limits and guidelines

The guidelines for health effects of whole-body vibration are well documented in Australian and International Standards. However, there is still much to be learnt about vibration dose/response relationships. In terms of health criteria, the current International Standard is an improvement on the Australian Standard which was based

on the 1985 International Standard. The new standard should provide a truer indication of injury risk due to vibration than the older standard.

The various State Occupational Health and Safety Regulations apply to truck drivers and under these Regulations employers are required to ensure that the systems of work and the working environment of the employee are without risks to health and safety. This would also apply to vibration exposure. However, the Australian Standard for whole-body vibration is not cited in State OH&S Regulations. This means that employers and employees would need to comply with guidelines from the most appropriate Standard available. Being the most recent standard, ISO 2631-1997 is likely to be considered most appropriate.

The fatigue limits in the current Australian Standard have been abandoned in the current International Standard because they were not supported by research. Further research is required to establish realistic fatigue limits.

The guidelines for comfort in the International Standard seem to be reasonably well founded (Griffin 1990) and could be useful in rating truck drivers vibration exposures especially if the contribution of vibration in all axes is included in the assessment. Comfort levels could possibly form the basis for fatigue limits although extensive research would be necessary to confirm such a link.

Conclusions and recommendations

There are at present no exposure limits for fatigue and vibration that are accepted by experts in the field. The limits for 'fatigue-decreased proficiency' in the current Australian Standard have been deleted from the new International Standard because they were not supported by research. There is anecdotal evidence that truck rides are often rough, uncomfortable and tiring. However, specific research on vibration and fatigue is limited and many authors have assumed a relationship without reference to supporting research. Some research shows a possible link between constant low frequency vibration and fatigue but more extensive research is required to establish meaningful exposure limits.

There is sufficient evidence that vibration exposure to drivers could be a health hazard particularly with regard to back problems. The relatively high vibration exposure levels combined with long exposure durations and prolonged sitting are likely to contribute to back pain and other health effects.

The current International Standard (ISO 2631 (1997) on whole-body vibration provides useable guidelines for vibration exposures and predicted health effects.

Recommendations for further research

1. An extensive experimental study on a possible relationship between vibration and fatigue could be considered, although it is likely that such research would be costly to conduct. Such a study is necessary to establish whether the effects of vibration would be noticeable among all other contributors to fatigue and each factor known to contribute to fatigue would need to be controlled for (eg time awake, time on task, rest and sleep, circadian factors).

2. There are limited published data on vibration exposure to drivers under Australian conditions. Available data indicates that exposures are likely to be high putting drivers at risk to health. A field survey of vibration levels experienced by heavy vehicle drivers under Australian conditions is recommended. Such data would be necessary to establish standards for trucks sold in Australia. A survey of this type need not be expensive because sufficient data could be obtained from a relatively small representative sample of drivers.

The survey would need to:

- provide information on typical vibration levels experienced by drivers under a range of operating conditions
- consider the practicality and relevance of exposure limits or guidelines for health, fatigue and comfort
- collect information on factors influencing vibration levels and ways to reduce vibration exposures to drivers
- develop simple and efficient vibration monitoring and reporting methods

Information collected from the survey could also form the basis of an information booklet for the trucking industry.

The report and its recommendations should be referred to the National Occupational Health and Safety Commission for broader dissemination to its key stakeholders and their advice should be sought on possible strategies for filling the gaps identified.

Contents

1	BACKGROUND.....	1
2	REVIEW METHODOLOGY	2
3	FACTORS INFLUENCING DRIVER FATIGUE	3
3.1	TEMPORAL FACTORS AND DRIVER FATIGUE	4
3.1.1	Length of Driving.....	4
3.1.2	Time of Day/Circadian Drive for Sleep	4
3.1.3	Shiftwork.....	5
3.2	DRIVER CHARACTERISTICS.....	6
3.2.1	Age and Gender.....	6
3.2.2	Medical Conditions/Sleep Factors	6
3.3	SUMMARY OF FATIGUE INFLUENCES	6
4	VIBRATION STANDARDS AND DOCUMENTED DRIVER EXPOSURE LEVELS.....	7
4.1	AUSTRALIAN STANDARD AS 2670.1 -1990.....	7
4.1.1	Limitations of the Australian Standard	7
4.2	INTERNATIONAL STANDARD ISO 2631-1, 1997	8
4.2.1	Comfort reactions to vibration environments – ISO 2631-1:1997, Annex C.....	9
4.3	COMPARISON OF THE AUSTRALIAN AND INTERNATIONAL STANDARD LIMITS.....	9
4.4	DOCUMENTED WHOLE-BODY VIBRATION EXPOSURE LEVELS OF HEAVY TRANSPORT VEHICLES.....	10
5	VIBRATION AND DRIVER FATIGUE	12
5.1	INTRODUCTION.....	12
5.2	SUMMARY OF RELEVANT RESEARCH.....	13
5.2.1	Low frequency vibration and fatigue	13
5.2.2	Changes to body chemistry due to vibration.....	13
5.2.3	Positive effects of vibration on driver alertness	14
5.2.4	Discomfort and vibration exposure during truck driving.....	15
5.2.5	Disorders arising from exposure to whole-body vibration (WBV).....	15
5.2.6	Two-up Driving and Vibration.....	16
5.3	VIBRATION AND DRIVER FATIGUE SUMMARY	17
5.3.1	Exposure limits and guidelines	18
6	CONCLUSION AND RECOMMENDATIONS.....	19
	REFERENCES	21
	APPENDIX 1 – AUSTRALIAN & INTERNATIONAL CONTACTS	26

1 BACKGROUND

In 1998 Roaduser International Pty Ltd was commissioned by the then Federal Office of Road Safety (FORS) to investigate alleged problems with the dynamic behaviour of certain types of heavy trucks. Following the investigation and a period of consultation and comment a final report was presented to the Minister for Transport and Regional Services (Sweatman & McFarlane, 2000). The Report and its Executive Summary, and a status report on the progress of actions arising out of the investigation, have been published on the web site of the Department of Transport and Regional Services (www.dotrs/land/truckrpt.htm and www.atsb/road/truck/sr1.cfm respectively).

The report made 16 recommendations which may be grouped into the following three broad categories:

- Actions to be taken on specific vehicles (recommendations 1, 2, 5 and 10)
- Improvements to vehicle design practice and standards (recommendations 3, 4, 6, 7, 8, 9, 12)
- Areas of possible further research (recommendations 11, 13, 14, 15, 16, reproduced at Attachment A).

This project concerns recommendations 11, 13 and 14 from the third group, dealing with further research into vibration through the driver's seat and its impact on driver fatigue and health, as identified in the report.

The management of driver fatigue has been a major research and policy theme in Australia for the past decade. Driver fatigue is acknowledged as a serious problem and is believed to contribute to between 4 and 30% of crashes, depending on how fatigue is defined. A new set of prescriptive hours limits has been developed by the National Road Transport Commission and adopted at least in part by most jurisdictions; two jurisdictions have developed a fatigue management Code of Practice based on their Occupational Health and Safety legislation; and a pilot of a Fatigue Management Program is in progress in Queensland. Other, parallel work on driver fatigue is in progress.

In the light of this, findings that relate vehicle vibration to driver fatigue and health are of concern. The extent to which vibration through the seat and possibly steering wheel contributes to driver fatigue is not known.

Several truck drivers' anecdotal evidence suggests that high levels of vibration contribute to driver fatigue. This link, however, does not appear to be well documented elsewhere in the research literature. ARRB's task was to determine to what extent vibration in heavy vehicle cabs contributes to driver fatigue or may constitute a health hazard. A further task was to establish and recommend vibration thresholds whereby exceeding the thresholds would constitute a fatigue or health hazard.

A literature search was conducted: the fatigue literature has been reviewed concurrently with literature pertaining to whole body vibration and its putative health and other effects on drivers. Assumptions have been drawn from the above literature to direct further investigation.

2 REVIEW METHODOLOGY

This study comprised:

1. A literature review to investigate the research on a possible link between vibration and driver fatigue. The research studies were critically evaluated to determine whether known contributing factors to fatigue had been accounted for within the study design. The fatigue literature was reviewed concurrently with the literature pertaining to vibration and health effects.
2. A review of existing data on driver exposure to vibration. These data were assessed for fatigue and health effects against the Australian Standard, AS 2670.1 - 1990, *Evaluation of human exposure to whole-body vibration*, and the International Standard, ISO 2631-1.2 - 1997, *Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration* or other national standards where appropriate.

Email communications with Australian and international fatigue experts were conducted to identify any studies on vibration and fatigue that may not have been published. A full list of contacts is in Appendix 1.

For the purposes of this study, the following research questions were asked:

- Has whole-body vibration exposure been measured in any studies of fatigue in drivers?
- Has fatigue as an outcome been measured within studies of whole-body vibration exposure?
- What evidence is there for a direct or indirect link between the development of fatigue and exposure of drivers to whole-body vibration?
- Do the existing exposure standards for whole-body vibration provide threshold levels for vibration-induced fatigue that reflect current knowledge?
- Are existing data sufficient to determine any relationship between driver vibration exposure, fatigue and possible health effects?
- Does vibration exposure to drivers present a health risk according to current exposure standards?

3 FACTORS INFLUENCING DRIVER FATIGUE

Considerable time and resources continue to be directed at the issue of managing driver fatigue. The main impetus for such research is the documented evidence of high levels of fatigue in the industry and the considerable cost of heavy vehicle crashes. The dimensions of heavy goods vehicles add to the problems associated with both the severity of crash outcomes and the public image of truck drivers in general (Mabbott & Newman, 2001). Hartley and Mabbott (1998) conducted a literature review for the 'Fatigue Task Force' in Western Australia and arrived at the list of contributions to driver fatigue as shown in Table 1.

Table 1: Factors identified as contributing to driver fatigue. Source: Hartley & Mabbott (1998).

Temporal Factors	Driver Characteristics	Environmental Factors	Sleep Factors
Driving between 2 AM & 5 AM	Young drivers up to 25 years of age	Driving in remote areas	Driving with sleep debt
Awake more than 16 hours before trip	Drivers older than 50 years old	Monotonous driving conditions	Sleep condition (eg. sleep apnoea)
Length of work before trip	Males	Long haul driving	Driving when normally asleep
Irregular shift pattern	Shiftworkers	Extreme climatic conditions	Predisposition to nodding off
Successive night shifts	Commercial drivers	Unfamiliar route	Driving after poor quality sleep
Time pressure	Medical conditions (eg. diabetes)	Lack of suitable rest stops	
Unexpected delays	After consuming alcohol		

At the time of the above review, the effects of vehicle vibration on driver fatigue had not been considered by the reviewers, thus, literature pertaining to vehicle vibration was not examined. It is likely that if there had been research studies performed on vibration and its contribution to driver fatigue, they would have been identified in the literature review performed at this time. There are very few references to vibration in the fatigue literature. The Fatigue Expert Group (2001) mention that environmental factors such as vibration, lead to driver fatigue. However, there are no references for the statement and one must assume that the statement has been included through anecdotal evidence.

The following review expands upon the above research (including more recent research) and investigates literature pertaining to the possible influence that vehicle seat and/or steering vibration has on driver fatigue.

3.1 Temporal Factors and Driver Fatigue

3.1.1 Length of Driving

In the past, fatigue research was generally directed at what was deemed to be the most relevant factor influencing driver fatigue – length of driving hours. For example, Australian legislated driving hours for truck drivers are partly based upon the assumption that driving in excess of 12 hours may lead to fatigue-related crashes. Regulations in other countries are generally based on the same assumption.

Some of the earlier work in the 1970s and 1980s suggested that driving in excess of eight hours starts to produce the effects of fatigue (Mackie & Miller, 1978; Lisper, Laurell & van Loon, 1986). Many different lengths of driving shifts have been studied, however, much of the research has been either limited to driving within the regulated hours of the jurisdiction, or longer shifts conducted on driving simulators. It has also become recognised that other factors will affect the outcomes of such research experiments.

For example, Lisper et al. (1986) found that subjects driving around a five kilometre test track experienced micro sleeps within 7 to 12 hours of commencing driving. Within those times, subjects fell asleep three times each (mean time between micro sleeps – 24 minutes) and were then given a brisk walk. The mean time to falling asleep again was 23 minutes. Of the initial 12 subjects, five quit the study between 8 and 12 hours of driving. Of the seven that fell asleep, five were from the group commencing at 1600 hrs and the other two started at 1000 hrs. As most of the falling asleep occurred between the 8th and 12th hours of driving, this would have been between 0000 hrs and 0400 hrs. This is a critical period known to be low in the circadian cycle.

3.1.2 Time of Day/Circadian Drive for Sleep

The circadian influence on human sleep patterns has been well documented and is a known contributor to driver fatigue. That humans have a diurnal cycle of sleep and wakefulness, creates a homeostatic drive for sleep if the human is awake when they would naturally be sleeping (Dinges, personal communication, 2000). It is at this time that the human must choose to fight the drive for sleep or to obtain some or all of the sleep necessary for recuperation. It is also at this point that there is the greatest chance of a fatigue related crash. A considerable amount of research has been conducted which illustrates the influence that the homeostatic drive for sleep has on driver performance. The following sections discuss examples of such research.

3.1.2.1 Subjective Questionnaire Research

Subjective evaluations of driving hours and shift patterns have been conducted to determine when drivers feel the most tired. Williamson, Feyer, Coumarelos and Jenkins (1992) interviewed 960 truck drivers in Australia, asking what times of the day or night they experienced fatigue. Not surprisingly, the majority stated that the period between midnight and 0600 hrs was the worst, whilst the second worst period was between lunch and 1800 hrs. Similar findings were experienced in a New York study by McCart, Hammer and Fuller (1998), in which drivers stated that the midnight to dawn period and the afternoon period were the two periods through which they feel most fatigued.

3.1.2.2 Objective Measures

The US/Canadian Driver Fatigue Alertness Study (DFAS) (Wylie et al. 1996) was one of the largest ‘over the road’ studies of driver fatigue to date. Around 4,000 hours of real-time testing was undertaken utilising truck drivers from Canada and the USA. Eighty drivers were monitored over 16 weeks, utilising objective measures such as: driving task performance; three surrogate performance tests (Code Substitution, Critical Tracking Test & Simple Response Vigilance Test); continuous video monitoring; and physiological measures (eg. Electroencephalogram, Electrocardiogram, Electrooculogram, Electromyogram, respiratory airflow and effort, body temperature).

The strongest and most consistent influencing factor for driver fatigue was the time of day. Video evidence of drivers’ faces showed considerably more drowsiness in the night than during the day. Midnight to dawn driving was also shown to have lowered performance levels on four measures. They were: Drowsy periods as seen on video; lane tracking; Code Substitution test scores, and average physiological sleep obtained prior to a trip. The time of day factor was a better predictor of decreased performance than hours spent driving or number of trips conducted.

The influence that time of day has on driver fatigue is often reflected in fatigue crash studies (eg. Pack et al. 1995, Folkard, 1997). Pack and his colleagues examined the temporal distribution of crashes judged by Police to be fatigue related. The resulting temporal distribution showed a high peak between midnight and late morning and a smaller peak in the early afternoon. This distribution was consistent with the results of sleep studies by Lavie (1986) whereby the peak fatigue crash periods were similar to the amounts and distribution of sleep obtained by subjects in the sleep experiment.

Folkard (1997) obtained trends from six published studies on fatigue crashes and transformed them into z-scores so that the large and small numbers of crashes in different studies did not have confounding influences on the results. Once the z-scores were plotted, a clear circadian effect was present. Similarly, Blower and Campbell (1998), in their investigation of fatalities and injuries of truck drivers in fatigue related crashes, found fatigue related crashes peaking between midnight and 0600 hrs.

Further support of the circadian influence can be found in Hamelin’s (1987) work, whereby driving through the night attracted a higher crash risk before 11 hours of driving than after 11 hours of driving. The opposite was noted for day driving. That is, the risk of crashing during the day was higher after 11 hours of driving.

3.1.3 Shiftwork

Shiftworkers have been the subject of many studies, especially as modern industries in particular utilise 24-hour operations to maximise the return on assets. For example, very few mines in Australia would not operate around the clock to maximise production. With the cost of mining machinery exceptionally high, a lot of production is required to make the initial cost practical. Long distance heavy vehicle operators work on a similar premise. That is, rolling stock should be kept operating around the clock to make most use of the asset, cover costs and return a profit. Further, the modern shift to ‘just in time’ deliveries has many vehicles operating through the night to have shelf items ready the following morning.

Kaneko and Jovanis (1992) studied truck operator driving patterns in USA in an attempt to test their potential effect on crash risk. A relative crash risk was analysed for each cluster of driving patterns using the number of trips resulting in a crash, the number of

trips not resulting in a crash and the cluster number. Of the nine identified patterns, the two determined to have the highest were through the period of midnight to dawn. Other studies have linked sleepy driving with rotating shifts, night shifts and irregular shifts (eg. Mitler et al. 1988, McCartt, Rohrbaugh, Hammer & Fuller, (2000).

3.2 Driver Characteristics

3.2.1 Age and Gender

The Hartley and Mabbott (1998) review noted that young males in particular, were one of the ‘at risk’ groups for fatigue crashes. Other research by McCartt et al. (2000) indicate that ‘older, long-time driver’ is one of the six factors found to be significant predictors of drivers having fallen asleep at the wheel at some time. The other five factors were: arduous work schedule, poor sleep on road, daytime sleepiness, symptoms of sleep disorder, and night-time drowsy driving.

3.2.2 Medical Conditions/Sleep Factors

Considerable fatigue research has focussed upon sleep disorders and sleep quality (eg. Stoohs et al. 1994, Maycock, 1995, Hillman, 1997). Maycock’s finding relating to sleep deprivation/poor quality of sleep and crash liability, was that drivers who snored, or were judged by interviewers to have a large collar size had an accident liability twice that of drivers without those characteristics. Similarly Stoohs et al. suggested that untreated sleep apnoea, sleep disordered breathing and snoring increase the risk of vehicle crashes. They also suggest that truck drivers are at increased risk of sleep apnoea (see also Swann, 2000 on sleep disorders and crash risk).

3.3 Summary of Fatigue Influences

The above research findings are presented as examples of the numerous factors known to impact on driver alertness levels. The influence of vibration has not been measured in the above research studies. No known attempts have been made in the past to specifically rank the contributors to driver fatigue in their order of influence. Many internationally known fatigue researchers will argue that; ‘time since last sleep’, ‘time of day’, ‘time spent working’ and ‘time and length of rest’ are the major contributors to driver fatigue. These are the main components of mathematical algorithms used to establish predicted performance of drivers by fatigue researchers (eg. Fletcher & Dawson, 1998, Belenky et al, 1998 and others).

Research to date has indicated that some factors are more fatiguing than others. For example, the US/Canadian study (Wylie et al, 1996) suggested that time of day influences were more fatiguing than the length of driving. It is known that there are a multitude of fatiguing influences present in the daily duties of heavy vehicle operators. However, it will be a long time before fatigue researchers will be able to determine a hierarchy of these influences.

4 VIBRATION STANDARDS AND DOCUMENTED DRIVER EXPOSURE LEVELS

4.1 Australian Standard AS 2670.1 -1990

The current Australian Standard on Whole-body vibration (AS 2670.1 – 1990) is based on the International Standard ISO 2631-1985. This standard provides limits against three criteria:

- 1 Exposure limits - relating to preserving health and safety and set at half the threshold of pain.
- 2 Fatigue-decreased proficiency boundary – concerned with the preservation of working efficiency and said to define a limit beyond which exposure to vibration might impair working efficiency for many kinds of tasks, particularly those in which time-dependent effects such as fatigue are known to worsen performance (e.g. vehicle driving).
- 3 Reduced comfort boundary – concerned with the preservation of comfort and based on studies in the transport industry related to difficulties carrying out such operations as eating, reading and writing rather than subjective discomfort response.

Different weightings based on the human body sensitivity are applied to vertical and horizontal vibrations. The vertical vibration (z-axis) criteria curve has its highest sensitivity between 4-8 Hz while horizontal vibration (x and y axes) is between 1-2 Hz.

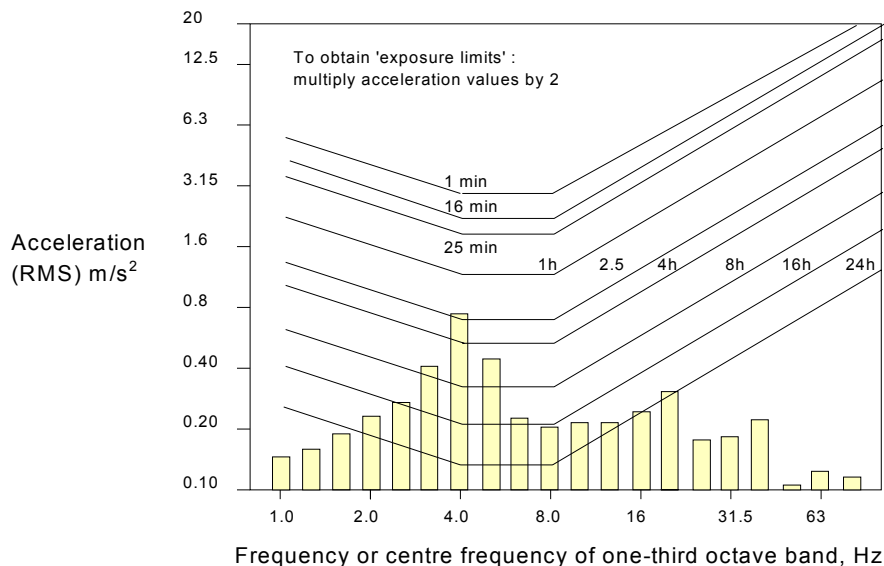


Figure 1: Australian Standard (AS 2670 –1990) vibration exposure limits for the fatigue-decreased proficiency boundary (z-axis) superimposed on a typical vibration spectrum.

4.1.1 Limitations of the Australian Standard

This Standard was based on ISO 2631-1 1985 which has since been superseded by ISO 2631-1, 1997. It is recognised (Griffin 1990, McPhee 2000), that assessment methods used in the Standard have limitations particularly for rougher rides where higher vibration peaks are present (AS 2670-1 1990, Clause 3.3).

There is not a satisfactory definition or scientific basis for the fatigue-decreased proficiency boundaries in the Australian Standard (Griffin 1990). The new International Standard

(ISO 2631-1, 1997, Foreword) has abandoned the ‘fatigue-decreased proficiency boundary’ and the previously used time dependences because the concept was not supported by research results. The Standard took a new approach in setting guidelines as outlined in Section 4.2 below.

4.2 International Standard ISO 2631-1, 1997

The International Standard ISO 2631-1, 1997, *Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration*, is quite different to the Australian Standard. It has abandoned the concept of fatigue-decreased proficiency and based the assessment criteria on health effects, comfort and perception and motion sickness.

The Standard uses a ‘caution zone’ for classifying vibration exposures that lie between specified limits depending on the exposure duration. Exposures above this caution zone are considered ‘likely to cause injury’. The Standard also gives guidelines for comfort and motion sickness.

For the assessment of shock type vibration, the new International Standard has incorporated the Vibration Dose Value (VDV). The vibration dose value is based on the fourth power instead of the second power used in the root mean square (r.m.s) averaging described above. Being a fourth power function, the VDV is more sensitive to peaks than the r.m.s method used in the Australian Standard and therefore a better indicator of rides that contain shocks or jolts and jars. The caution zone is reached when the VDV is $8.5 \text{ m/sec}^{1.75}$ and the likely health risk zone when the VDV is $17 \text{ m/sec}^{1.75}$.

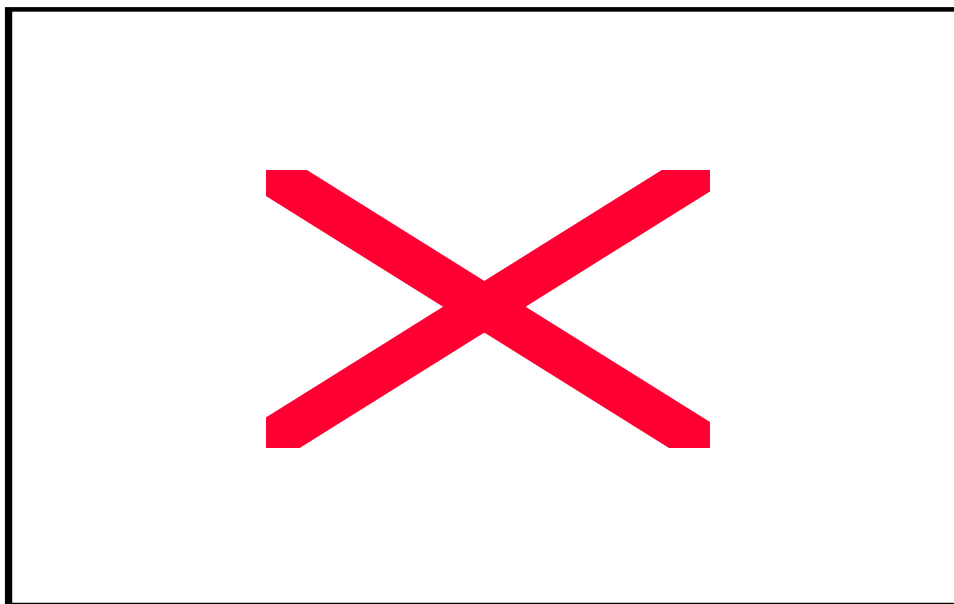


Figure 2: Health guidance zones, ISO 2631-1, 1997.

4.2.1 Comfort reactions to vibration environments – ISO 2631-1:1997, Annex C.

Less than 0.315 m/s ²	not uncomfortable
0.315 m/s ² to 0.63 m/s ²	a little uncomfortable
0.5 m/s ² to 1 m/s ²	fairly uncomfortable
0.8 m/s ² to 1.6 m/s ²	uncomfortable
1.25 m/s ² to 2.5 m/s ²	very uncomfortable
Greater than 2 m/s ²	extremely uncomfortable

4.3 Comparison of the Australian and International Standard Limits

The International Standard tends to be more stringent than the Australian Standard in its assessment of health effects. The guidance information and exposure criteria in the International Standard reflect current research and are recognised as being more protective in terms of health effects than the Australian Standard, particularly for vibration containing high peaks or shocks. The International Standard no longer provides guidance on fatigue and proficiency but has retained guidance on comfort levels and added guidance on motion sickness. It should be noted that the comfort level of the International Standard is the same as the 8-hour fatigue limit of the Australian Standard (0.315 m/s²).

The following table compares the permissible 8-hour and 12-hour average vibration exposure levels for the Australian and International Standards with actual truck driver's exposure levels.

Table 2: Vibration limits for 8-hour and 12-hours exposures compared with typical truck vibration levels.

Exposure duration	AUSTRALIAN STANDARD AS 2670.1 –1990 (average rms acceleration limits)			INTERNATIONAL STANDARD ISO 2631-1, 1997 (average rms acceleration limits)			Typical heavy truck vibration levels ¹
	Health limit	Fatigue limit	Comfort limit	Likely health risk	Caution zone	Comfort level	
8-hours	0.63 m/s ²	0.315 m/s ²	0.1 m/s ²	0.8 m/s ²	0.5 m/s ²	0.315 m/s ²	0.72 m/s ² (mean, z-axis)
12-hours	0.5 m/s ²	0.25 m/s ²	0.08 m/s ²	0.7 m/s ²	0.4 m/s ²	0.315 m/s ²	0.42 – 2.1 m/s ² (range, z-axis)

Table note 1. Mean & range of vibration levels listed in Table 2.

4.4 Documented whole-body vibration exposure levels of heavy transport vehicles.

The results of several surveys of whole-body vibration exposure levels are listed in Table 3. Most data are for vertical (z-axis) vibration direction with limited data for the fore to aft (x-axis) direction. The values listed represent a range of exposure conditions in different vehicles travelling on a variety of good and poor roads.

The typical range of exposure levels for a heavy transport truck is approximately 0.42 to 2.0 m/s² in the vertical axis. The mean value of operational exposure levels (excluding test tracks) listed in Table 2 is 0.72 m/s² in the z-axis and 0.78 m/s² in the x-axis. This puts the average truck driver exposure within the caution zone of the International Standard for an 8-hour shift and just into the likely health risk zone for a 12-hour shift. Exposure periods of 12 hours are common in the transport industry (Sweatman & McFarlane, 2000). Some of the rougher truck rides will be in the some likely health risk zone in less than 8 hours. Most vehicle rides will exceed the comfort level of 0.315 m/s² after a few hours. Many truck rides would also exceed the Australian Standard limits for health, fatigue and comfort.

Highest levels of vibration were found to be in the range 2 - 4 Hz for the vertical direction and 10 -15 Hz in the fore to aft direction (Sweatman & McFarlane, 2000). Other surveys (Paddan, Griffin, Burdorf) had similar findings. Sweatman & McFarlane found that the low frequency vibration around 2.5 Hz is due to a bouncing motion that occurs in response to road roughness involving deflection of the front tyres. High vertical seat pad vibration is due to relatively stiff front suspension and poorly-damped bounce of the front axle. High fore to aft vibration is due to less stiff front suspensions and may be influenced by chassis bending vibrations.

Steering wheel accelerations were found to be higher than the seat vibrations in some cases (Sweatman & McFarlane, 2000). Most vibration was in the range 8 – 15 Hz at levels in the range 0.4 – 1.0 m/s². Given the long exposure durations there may be a small risk of adverse effects on the hand/arm at the higher exposure levels.

Table 3: Whole-body vibration exposure levels measurements in truck drivers

Authors	Publication	Vibration exposure values¹	Comments
Griffin, M.J	Handbook of Human Vibration (1990)	z-axis- mean 1.056 m/s ² VDV 2.9 m/s ^{1.75} (x-axis) 1.087 m/s ² (back rest mean)	Average results for trucks tested on rough test track. Fore and aft (x-axis) backrest vibration caused most discomfort. Exposure limit reached in 4 hours. Fatigue limit reached in 1.5 hours British Std health limit in 2.5 hours
Paddan, G, S et al	British HSE contract report (1999)	z-axis- mean 0.65 m/s ² min 0.42 m/s ² max 1.28 m/s ²	A variety of lorries (nine) tested under normal operating conditions-on road in Britain. Almost all measured exposures were in the ISO caution zone, some were in the likely health risk zone. The z-axis was worst
Sweatman & McFarlane	Investigation into the Specification of Heavy Trucks & Consequent Effects on Truck Dynamics & Drivers (2000)	z-axis- 0.64 to 1.60 m/s ² mean 0.88 m/s ² x-axis- 0.50 to 1.12 m/s ² mean 0.78 m/s ²	Study of vibration characteristics of selected heavy transport trucks under operating conditions. All measurements above ISO comfort level (0.315 m/s ²) All vehicle rides were in the ISO caution zone and three were in the likely health risk zone for an 8 hour exposure.
Burdorf & Swuste	Annals of Occupational Hygiene (1993)	z-axis 0.51 to 0.99 m/s ² mean 0.64 m/s ²	All (9 trucks) measurements exceed ISO comfort levels (0.315 m/s ²). All fall within the caution zone and two are in the likely health risk zone of the 1997 ISO standard.
Mistrot et al	Ergonomics 1990	combined axes 0.6 to 2.1 m/s ²	Vertical and fore to aft vibration dominated. All measurements would be in or above the ISO 1997 caution zone.
Cooper and Young	TRRL report 1980	levels up to 2 m/s ²	Truck drivers could suffer some decreased proficiency after about 4 hours at the highest vibration levels measured

Table note 1. Vibration exposure expressed as rms acceleration unless otherwise stated.

5 VIBRATION AND DRIVER FATIGUE

5.1 Introduction

The relationship between vibration exposure and fatigue has not been investigated to any great extent. Few published articles were found that were the result of studying effects of vibration on driver fatigue. Wilson and Horner (1979) obtained 3,608 questionnaire responses from articulated truck drivers in the US. Vibration was always noticed by 71% of the drivers in empty vehicles and 47% in loaded vehicles. Within the first three hours of driving, 79% of drivers were aware of vibration and were in the uncomfortable to fairly uncomfortable range. Over 50% of the drivers stated that fatigue was a major problem. However, measures of fatigue were subjective. The feeling of subjective fatigue does not always correlate to objective measures of fatigue (eg. Mabbott & Newman, 2001).

Seemingly conflicting findings of the effects of vibration have been reported. Some studies identified vibration as a stimulant and others as inducing drowsiness. Vibration is thought to interact with the brain through the non-auditory labyrinth, proprioceptors, visual and skin mechanoreceptors and can have different effects depending on the type of vibration experienced.

Landstrom and Landstrom (1985) investigated the effects of different types of vibration exposure both in laboratory experiments and in field studies of helicopter pilots. Their studies supported the view that random and stimulating vibration exposure can act to increase alertness and that low frequency monotonous vibration has the opposite effect by increasing drowsiness. Similar findings applied to exposure to low frequency noise or infrasound. Similarly, several other researchers (Mackie et al, 1974 & Petit & Tarriere, 1992) have found that intermittent and random vibration exposure can increase alertness.

The effect of vibration on body chemistry was investigated by Kamenski and Nosova (1989). Changes to the body metabolism as a result of exposure to whole-body vibration exposure were investigated in an attempt to explain possible mechanisms for the fatigue effects of vibration.

Discomfort caused by excessive vibration is also thought to contribute to fatigue by some researchers. The high fore to aft vibration reported in some studies is recognised as causing more discomfort than vertical vibration and may also interfere with the ability to control the vehicle if severe enough.

No studies of hand-arm vibration and fatigue have been identified during the literature search. Prolonged exposure to hand-arm vibration can result in a variety of adverse health effects but these are more relevant to the use of vibrating tools at higher vibration levels than those associated with truck driving. However, steering wheel vibration levels as high as 1 m/s^2 have been reported in one study (Sweatman & McFarlane, 2000). Hand-arm vibration at this level may present a slight risk of injury considering the long exposure durations involved in truck driving. In another study of hand-arm vibration the researchers investigated possible changes in grip strength due to steering wheel vibration but concluded there were none.

5.2 Summary of relevant research

5.2.1 Low frequency vibration and fatigue

In laboratory experiments, Landstrom and Landstrom (1985) exposed thirty subjects to low frequency sinusoidal vibration and random whole body vibration in the vertical direction in order to detect any changes in wakefulness/fatigue. Twenty subjects were exposed to sinusoidal vibration at 3 Hz and 28 subjects were exposed to random vibration 2-20 Hz. In both cases the average vibration exposure level was 0.3 m/s^2 (rms). The experimental work was divided into 7 periods each of 15-minute duration. Wakefulness/fatigue was assessed by monitoring changes in the brain's alpha and theta activity as measured by EEG. Increased fatigue is detected by combined increased theta and decreased alpha activity. In addition, the subjects' pulse rate was measured by ECG.

Results showed an increased theta activity and decreased alpha activity for both the random vibration group and the sinusoidal vibration group. However, effects were much greater for those exposed to the low frequency sinusoidal vibration. Stopping and starting the vibration stimulation increased alertness. Pulse rates were lowered during vibration exposure in both groups but to a greater extent in the sinusoidal group. The authors concluded that 'The results obtained support the hypothesis that monotonous low frequency vibration may introduce a reduction in alertness, the effect being less pronounced during random compared with sinusoidal vibration'. The authors also commented that they believed the experimental results supported the theory that activation of the brain occurs in the case of intermittent and random vibration stimulation and that drowsiness may be induced in cases of decreased sensory stimulation or of monotonous stimulation, such as that provided by a low frequency sinusoidal vibration.

Field studies of helicopter pilots (Landstrom and Lofstedt 1987) were undertaken to confirm laboratory findings relating wakefulness and low frequency vibration. Low frequency noise and vibration were monitored during test flights over periods of 4 hours and 2 hours. Analysis of wakefulness/fatigue was based on EEG and EKG recordings with electrodes attached to the pilot's head (occipital location P4-02) and chest for monitoring heart activity. Highest vibration levels were recorded in the vertical direction at levels of between $0.09 - 0.90 \text{ m/s}^2$ with the dominant frequency around between 8 Hz and 16 Hz. The wakefulness/fatigue levels of the pilots were high during takeoff and landing and decreased during the flight. It was concluded that the low frequency noise and vibration were important factors leading to fatigue of pilots. However, the authors recognised that other factors such as monotony and boredom are also important factors.

Lofstedt and Landstrom (1987) investigated driver alertness of two truck drivers under typical driving conditions. They found that the drivers became more readily fatigued when driving trucks that generated a high level of low-frequency noise.

5.2.2 Changes to body chemistry due to vibration

Kamenski and Nosova (1989) conducted a series of experiments on 22 male subjects who were exposed to whole-body vibration with the characteristics typical of road transport vehicles at levels ranging between $0.6 - 1.4 \text{ m/s}^2$. The subjects were exposed to vibration for periods of 1 hour while sitting in a rigid chair on a vibrating platform in the laboratory. Noise levels did not exceed 58 dB(A) during the trials. Blood and urine

samples were taken before and immediately after exposure. The blood was analysed for acetylcholine and the acetylcholinesterase activity, the lactic acid concentration, the level of cortisol, insulin and aldosterone and the content of non-esterified fatty acids. The urine was analysed for adrenaline and noradrenaline, the level of electrolyte excretion (sodium and potassium) and the content of cyclic 3' – 5' – adenosine monophosphate (AMF). Exposure to whole-body vibration caused noticeable shifts in the metabolic and neurohormonal status of the subjects. There was a tendency for a reduction in the acetylcholine content in the blood and the lactic acid concentration was increased by 25.2% immediately after the end of exposure and by 30.8% after 30 minutes. There was a significant drop in the AMF level of 50.3%. The adrenaline excretion after exposure was unchanged while that of noradrenaline was somewhat reduced. These changes were interpreted by the authors as being related to the adaptive regulatory function of the body under exposure to whole-body vibration.

The increase in lactic acid is due to muscle activity in the spine directed at maintaining posture under exposure to vibration. The reduction of AMF was considered to be the most significant result of the exposure because this nucleotide is involved in the energy production processes of the body and modifies many physiological reactions in response to vibration exposure. The authors concluded that changes in body metabolism may explain the fatigue effects.

5.2.3 Positive effects of vibration on driver alertness

Grether (1971) reviewed several papers relating to studies on vibration and primary central neural processing, conducted as far back as 1938. Grether summarised the results of the studies indicating that reaction time, pattern recognition and monitoring, appear to be resistant to degradation during vibration.

Petit and Tarriere (1992) performed 108 experiments on 36 subjects in each of the following conditions; reference - noise (80 dBA inside car) - heat (30° C) for half of them, and vibration (road spectrum) – vibration + noise + heat for the other half. The subjects were to operate a driving simulator for two hours in each condition. The measures taken were, electroencephalograms of cerebral waves, electromyograms of heart rates, number of times subjects left the simulated roadway, and detection of light signals. They found that noise and vibration had a small effect on alertness while heat detracted greatly from alertness. They also noted that vibration resulted in a defensive reaction of postural muscles, increasing blood flow and heart rate.

Heat increased the number of times subjects left the road and the time taken to detect light signals. Conversely, vibration reduced the number of times subjects left the road. The effect of vibration, and the effects of vibration, noise and heat together, greatly increased the time for detection of light signals. The authors conclude that heat is the most negative parameter in terms of cerebral alertness. Further, they offer the interpretation that vibration and noise exert a stimulating effect on the central nervous system, offsetting the inhibiting influence of heat.

Mackie, O'hanlon and McCaunley (1974; cited in Petit & Tarriere, 1992) also studied the same three environmental stressors as in the above study. They found that heat would affect drivers' physiological states and performances if it exceeded 27°C to 30°C. The combined effect of vibration and noise caused no noticed fall in performance. Mackie et al. concluded that adaptation to moderate levels of vibration and noise is likely.

5.2.4 Discomfort and vibration exposure during truck driving

Randall (1992) reviewed vibration exposure data from surveys of truck drivers and compared the exposures with the International Standard (1985 version) comfort criteria. Measured vibration levels ranged from 0.2 m/s^2 to 1.4 m/s^2 in the vertical direction. The author concluded that according to the International Standard comfort criteria, truck drivers suffer severe discomfort within minutes on very rough roads, within an hour or two on poor roads and within a few hours on good roads.

Mistrot et al (1990) investigated the correlation between subjective comfort ratings and vibration exposure in the vertical axis as well as the combined vertical and horizontal axes. Subjects were exposed to a range of whole-body vibration levels and frequencies on a test rig and then asked to rate their comfort levels on a line representing low and high discomfort levels at the extremes. A field study was also conducted to test subjects over a range of different road conditions. Vibration levels ranged from 0.6 to 2.1 m/s^2 for the road trials with the highest levels in the z-axis and x-axis. The authors found that ISO 2631 (1985), underestimates the discomfort due to vibration in the fore to aft direction or x-axis particularly at 3.15 Hz and that the severity of horizontal vibration in trucks is underestimated by this standard. It was concluded that the best method to predict the vibration discomfort experienced by seated persons exposed to multi-axis vibration is to calculate the square root of the sum of the squares of the weighted accelerations measured along each axis.

The Vibration Dose Value (VDV) used in the ISO 2631 (1997) standard has been found to correlate well with driver ratings of road roughness particularly for rough rides (McPhee, Foster & Long). Griffin (1990) has found that the VDV is a useful measure of increasing discomfort with increasing duration of exposure and a good indicator of subjective reaction to shocks.

5.2.5 Disorders arising from exposure to whole-body vibration (WBV)

The effects on humans of exposure to vibration generally at best may be discomfort and interference with activities; at worst may be injury or disease.

Vibration is believed to cause a range of problems. These include:

- disorders of the joints and muscles and especially the spine (WBV)
- disorders of the circulation (hand-arm vibration)
- cardiovascular, respiratory, endocrine and metabolic changes (WBV)
- problems in the digestive system (WBV)
- reproductive damage in females (WBV)
- impairment of vision and/or balance (WBV)
- interference with activities
- discomfort

The most frequently reported problem from all sources of WBV is low-back pain arising from early degeneration of the lumbar system and herniated lumbar disc. Muscular fatigue and stiffness have also been reported. Laboratory studies have associated the degeneration of lumbar vertebrae after intense long-term exposure to WBV. However,

despite this, not a lot is known about the specific effects of exposure WBV on the bones, muscles and joints particularly the spine.

The most frequently reported adverse effect from all sources of WBV is low back pain and sciatica thought to arise from premature degeneration of the joints and end plates of the spinal vertebrae and herniated lumbar disc (Wikström 1978; Wilder et al 1982; Frymoyer et al 1983; Kjellberg and Wikström 1985; Kjellberg, Wikström and Dumberg 1985; Seidel, Bluethner and Hinz 1986; Dupuis and Zerlett 1987; Hulshof and Van Zanten 1987; Kjellberg and Wikström 1987; Boshuizen, Hulshof and Bongers 1990; Dupuis, Hartung and Haverkamp 1991; Pelmear, Roos and Maehle 1992, Seidel 1993; Wikström, Kjellberg and Landström 1994). Paraesthesia of the limbs also has been reported (Dupuis and Zerlett 1987). Laboratory studies have noted degeneration of the lumbar vertebrae after intense long-term exposure to WBV (Seidel and Heide 1986).

In a questionnaire survey of back pain symptoms in professional truck drivers, Masabumi Miyamoto et al (2000) found that the prevalence of back pain was 50.3%. Three factors related significantly to the prevalence of low back pain, these were: irregular duty time, short resting time and long driving time in a day. Eighty-one of the 153 drivers pointed out the relationship between low back pain and work, especially when vibration and road shock is involved. The authors suggested that their study supported the view that vibration is an obvious risk factor of low back pain.

Dupuis and Zerlett (1987) noted that reports of back pain were age-related, i.e. reports of low back pain increased with age, as might be expected in the general population (Wikström 1978; Andersson 1981). However, there is evidence that back pain is occurring earlier than expected for workers exposed to WBV (Boshuizen, Bongers and Hulshof 1992). In the Netherlands, Germany and the USA studies of people exposed to vibration at work indicate that, when compared with controls, premature spinal degeneration and/or low back pain was more prevalent in crane operators (Bongers et al 1988a,b; Boshuizen et al 1990a,b; Burdorf and Zondervan 1990); helicopter pilots (Bongers et al 1990; Boshuizen, Bongers and Hulshof 1990b); subway train operators (Johanning 1991); tractor drivers (Boshuizen et al 1990 a,b; Boshuizen, Bongers and Hulshof 1992); and forklift drivers (Brendstrup and Biering-Sørensen 1987).

Prolonged sitting, poor working postures and inadequate ergonomic conditions (including poor seat and cab design) also are believed to contribute to back pain and are usually found in association with WBV exposure (Kelsey and Hardy 1975; Troup 1978; Wikström 1978; Bongers et al 1988a, 1990; Riihimäki et al 1989; Burdorf and Zondervan 1990; Johanning 1991; Boshuizen, Bongers and Hulshof 1992). As well, many driving jobs involve manual handling (Wikström 1978; Riihimäki et al 1989).

5.2.6 Two-up Driving and Vibration

Two-up drivers are utilised to maximise the asset of the rolling stock, especially on very long distance trips. As one driver is driving, the other will be obtaining sleep in the sleeper berth of the truck cabin. As the truck will be driven for nearly all of the 24-hour day, high arousal levels for both drivers are essential. Complications can arise when one or both drivers cannot sleep adequately due to several factors. These may include but may not be limited to; lack of trust that the driver will pull over if sleepy, lack of trust in the driving abilities of the driver, large movements of the truck, noise, heat and vibration.

The case for obtaining adequate duration and quality of sleep is paramount as split-sleep is known to be an issue with driver fatigue (eg. Arnold et al. 1996, McCartt, Rohrbaugh, Hammer & Fuller, 2000). In a study to determine whether vibrations from heavy road traffic disturbed the sleep of subjects, Arnberg, Bennerhult and Eberhardt (1990) tested subjects attempting to sleep through periods of vertical and horizontal vibrations. The small group of subjects were administered different levels of vibration in a pilot study. The results showed that noise plus vibration caused arousal in sleep, more so than noise alone. Further, vibration without noise caused changes in the stages of sleep for the subjects. The authors concluded that this may be due to the vibrations being more threatening without the identifying stimulus of noise. It is unknown whether two-up drivers experience vehicle vibration to the extent that it disturbs sleep, or whether a level of habituation occurs.

5.3 Vibration and Driver Fatigue Summary

Past research has associated whole-body vibration exposure with a number of adverse effects on the human body. The effects of vibration on the lower back and spine have been extensively researched and documented. Effects on the gastrointestinal system have received less attention but are considered by some to be significant. In many studies a relationship between vibration and fatigue has been assumed without supporting research and often based only on anecdotal evidence. The study of fatigue as it relates to vibration is complex and there is limited research available. However, the literature review has identified a few studies showing a possible association between fatigue and low frequency vibration that is typical of the vibration frequencies experienced by truck drivers. These findings could form the basis of further research in this area.

The following points summarise the findings of the literature review:

- Typical whole-body vibration exposure levels of heavy vehicle drivers are in the range 0.4 – 2.0 m/s² with a mean value of 0.7 m/s² in the vertical (z-axis). Vertical vibration is highest in the frequency range 2 – 4 Hz.
- The average whole-body vibration level experienced by drivers of heavy transport vehicles exceed health, fatigue and comfort limits of the Australian Standard and most exposures are within the Caution zone (for health) according to the current International Standard. Many typical exposures will reach the likely health risk zone of the International Standard. According to these standards, many truck drivers are at risk of incurring adverse health effects from prolonged exposure to vibration.
- There is some laboratory and field research that supports a relationship between low frequency vibration (3 Hz) and increased fatigue or drowsiness. This may have implications for heavy vehicle truck drivers who usually experience vibration level around this frequency while driving.
- Intermittent and random vibration can have a stimulating or wakening effect.
- Vibration exposure has been found to cause changes to body metabolism and chemistry that could lead to fatigue effects.
- There is evidence that truck drivers have back complaints that could be partly attributable to whole-body vibration exposure.

- Comfort limits of both Australian and International Standards are exceeded by most vehicle rides.
- The health effects of whole-body vibration has been extensively researched and adverse effects have been established. Truck drivers shown many of the symptoms of adverse health effects associated with whole-body vibration exposure.

5.3.1 Exposure limits and guidelines

The guidelines for health effects of whole-body vibration are well documented in Australian and International Standards and there is still much to be learned about vibration dose/response relationships. In terms of health criteria, the current International Standard is an improvement on the Australian Standard which was based on the 1985 International Standard. The new standard should provide a truer indication of injury risk due to vibration than the older standard.

Various State Occupational Health and Safety Regulations apply to truck drivers and under these Regulations employers are required to ensure that the systems of work and the working environment of the employee are without risks to health and safety. This would also apply to vibration exposure. However, the Australian Standard for whole-body vibration is not cited in State OH&S Regulations. This means that employers and employees would need to comply with guidelines from the most appropriate Standard available. Being the most recent standard, ISO 2631-1997 is likely to be considered most appropriate.

The fatigue limits in the current Australian Standard have been abandoned in the current International Standard because they were not supported by research. Further research is required to establish realistic fatigue limits.

The guidelines for comfort in the International Standard seem to be reasonably well founded (Griffin 1990) and could be useful in rating truck drivers vibration exposures especially if the contribution of vibration in all axes is included in the assessment. Comfort levels could possibly form the basis for fatigue limits although extensive research would be necessary to confirm such a link.

6 CONCLUSION AND RECOMMENDATIONS

There are at present no exposure limits for fatigue and vibration that are accepted by experts in the field. The limits for ‘fatigue-decreased proficiency’ in the current Australian Standard have been deleted from the new International Standard because they were not supported by research. There is anecdotal evidence that truck rides are often rough, uncomfortable and tiring. However, specific research on vibration and fatigue is limited and many authors have assumed a relationship without reference to supporting research. Some research shows a possible link between constant low frequency vibration and fatigue but more extensive research is required to establish meaningful exposure limits.

There is sufficient evidence that vibration exposure to drivers could be a health hazard particularly with regard to back problems. The relatively high vibration exposure levels combined with long exposure durations and prolonged sitting are likely to contribute to back pain and other health effects.

The current International Standard (ISO 2631-1997) on whole-body vibration provides useable guidelines for vibration exposures and predicted health effects.

6.1 Recommendations for further research

1. An extensive experimental study on a possible relationship between vibration and fatigue could be considered, although it is likely that such research would be costly to conduct. Such a study is necessary to establish whether the effects of vibration would be noticeable among all other contributors to fatigue and each factor known to contribute to fatigue would need to be controlled for (eg time awake, time on task, rest and sleep, circadian factors).

2. There are limited published data on vibration exposure to drivers under Australian conditions. Available data indicates that exposures are likely to be high putting drivers at risk to health. A field survey of vibration levels experienced by heavy vehicle drivers under Australian conditions is recommended. Such data would be necessary to establish standards for trucks sold in Australia. A survey of this type need not be expensive because sufficient data could be obtained from a relatively small representative sample of drivers.

The survey would need to:

- provide information on typical vibration levels experienced by drivers under a range of operating conditions
- consider the practicality and relevance of exposure limits or guidelines for health, fatigue and comfort
- collect information on factors influencing vibration levels and ways to reduce vibration exposures to drivers
- develop simple and efficient vibration monitoring and reporting methods

Information collected from the survey could also form the basis of an information booklet for the trucking industry.

The report and its recommendations should be referred to the National Occupational Health and Safety Commission for broader dissemination to its key stakeholders and their advice should be sought on possible strategies for filling the gaps identified.

REFERENCES

- ANDERSSON, G.B.J. (1981). Epidemiologic aspects on low-back pain in industry. *Spine*, Vol. 6 (1), pp. 53-60.
- ARNOLD, P. K., HARTLEY, L. R., PENNA, F., HOCHSTADT, D., CORRY, A & FEYER, A. M. (1996). *Fatigue in the Western Australian transport industry: The driver's perspective*. Report Number 118. Institute for Research in Safety & Transport, Murdoch University, Western Australia.
- AS 2670.1 - 1990, *Evaluation of human exposure to whole-body vibration, Part 1: General requirements*. Standards Australia, Sydney.
- BELENKY, G., BALKIN, T. J., REDMOND, D. P., SING, H. C., THOMAS, M. L., THORNE, D. R. & WESTENSTEN, N. J. (1998). Sustaining performance during continuous operations: The US Army's sleep management system. **In** HARTLEY, L. R. (Ed.) *Managing Fatigue in Transportation. Proceedings of the Third International Conference on Fatigue and Transportation, Fremantle, Western Australia*. Elsevier Science Ltd., Oxford UK.
- BLOWER, D. & CAMPBELL, K. (1998). Fatalities and Injuries in Truck Crashes by Time of Day. Report No. FHWA-MC-99-098 (Interim Report), Federal Highway Administration Office of Road Carriers, Washington DC, USA.
- BONGERS, P. M., BOSHUIZEN, H. C. & HULSOFF, C. T. J. (1990). Self-reported back pain in tractor drivers exposed to whole-body vibration. *Int. Arch. Occup. Environ. Health*, Vol. 62, pp. 109-115.
- BONGERS, P. M., BOSHUIZEN, H. C., HULSOFF, C. T. J. & KOEMEESTER, A. P. (1988). Back disorders in crane operators exposed to whole-body vibration, *Int. Arch. Occup. Environ. Health*, Vol. 60, pp.129-137.
- BONGERS, P. M., BOSHUIZEN, H.,C., HULSOFF, C.,T.,J. & KOEMEESTER, A.,P. (1988). Long-term sickness absence due to back disorders in crane operators exposed to whole-body vibration. *Int. Arch. Occup. Environ. Health*, Vol. 61, pp. 59-64.
- BONGERS, P. M., HULSOFF, C. T. J.; DIJKSTRA, L.; BOSHUIZEN, H. C.; GROENHOUT, H. J. M. & VALKEN, E.; (1990), Back pain and exposure to whole body vibration in helicopter pilots. *Ergonomics*, Vol. 33 (8), pp. 1007-1026.
- BOSHUIZEN, H. C., BONGERS, P.M . & HULSOFF, C. T. J. (1992). Self-reported back pain in fork-lift truck and freight-container tractor drivers exposed to whole-body vibration. *Spine*, Vol. 17 (1), pp. 59-65.
- BOSHUIZEN, H. C., HULSOFF, C. T. J. & BONGERS, P. M. (1990). Long-term sick leave and disability pensioning due to back disorders of tractor drivers exposed to whole-body vibration. *Int. Arch. Occup. Environ. Health*, Vol. 62, pp. 117-122.
- BRENDSTRUP, T. & BIERING-SORENSEN, F. (1987). Effect of fork-lift driving on low-back trouble. *Scand. J. Work. Environ. Health*, Vol. 13, pp. 445-452.
- BURDOF, A. & ZONDERVAN, H. (1990). An epidemiological study of low-back pain in crane operators. *Ergonomics*, Vol. 33 (8), pp. 981-987.
- BURDORF, A., SWUSTE, P. (1993). The effect of seat suspension on exposure to whole-body vibration of professional drivers. *Ann. Occup. Hyg.* Vol 37, (1), pp. 45-55.

- CHARLTON, S. G. & BASS, P. H. (1998). The interaction of driver, vehicle and road contributing factors in truck crashes. *Road Safety Research, Policing, Education Conference*, Vol 2, pp. 209-213. Land Transport Safety Authority, Wellington, New Zealand.
- COOPER, D. & YOUNG, J. (1980). *Road Surface Irregularity and Vehicle Ride, Part 3 – Riding Comfort in Coaches and Heavy Goods Vehicles. TRRL Supplementary Report 560*. Transport and Road Research Laboratory, Crowthorne, Berkshire Great Britain.
- DINGES, D. F. & MALLIS, M. M. (1998). Managing fatigue by drowsiness detection: Can technological promises be realised? **In** HARTLEY, L. R. (Ed.) *Managing Fatigue in Transportation. Proceedings of the Third International Conference on Fatigue and Transportation, Fremantle, Western Australia*. Elsevier Science Ltd., Oxford UK.
- DUPUIS, H., HARTUNG, E. & HAVERKAMP, M. (1991). Acute effects of transient vertical whole-body vibration. *Int. Arch. Occup. Environ. Health*, Vol. 63, pp. 261-265.
- FATIGUE EXPERT GROUP (2001). *Options for Regulatory Approach to Fatigue in Drivers of Heavy Vehicles in Australia and New Zealand*. National Road Transport Commission, Australian Transport Safety Bureau and Land Transport Safety Authority. Report CR 202, National Road Transport Commission, Victoria.
- FLETCHER, A. & DAWSON, D. (1998). A workrelated fatigue model based on hours of work. **In** HARTLEY, L. R. (Ed.) *Managing Fatigue in Transportation. Proceedings of the Third International Conference on Fatigue and Transportation, Fremantle, Western Australia*. Elsevier Science Ltd., Oxford UK.
- FOLKARD, S. (1997). Black times: Temporal determinants of transport safety. *Accident Analysis and Prevention*, Vol 29 (4), pp. 417-430.
- GRETHER, W. F. (1971). Vibration and human performance. *Human Factors*, Vol. 13 (3), pp. 203-216.
- GRIFFIN M. J. AND WHITHAM E. M. (1980a). Discomfort produced by impulsive whole-body vibration. *Journal of Acoustical Society of America*, Vol. 68, pp. 1277-1284.
- GRIFFIN M. J. AND WHITHAM E. M. (1980b). Time-dependency of whole-body vibration discomfort. *Journal of Acoustical Society of America*, Vol. 68, pp. 1522-1523.
- GRIFFIN, M. J. (1990). *Handbook of Human Vibration*, Academic Press Limited.
- HAMELIN, P. (1987). Truck driver's involvement in traffic accidents as related to their shiftworks and professional features. *Symposium on the Role of Heavy Freight Vehicles in Traffic Accidents*, Montreal, Canada, Vol 2 (3), pp 107-130. Roads and Transportation Association of Canada (RTAC), Ottawa, Ontario, Canada.
- HARTLEY, L. R. & MABBOTT, N. A. (1998). *Fatigue-Related Crashes: A Summary of Characteristics and Prevalence*. Report No. 130, Institute for Research in Safety and Transport, Murdoch University, Murdoch, Western Australia. ISBN: 869056042.

- HARTLEY, L. R., HORBERRY, T., MABBOTT, N. A. & KRUEGER, G. P. (2000). *Review of Fatigue Detection and Prediction Technologies*. National Road Transport Commission, Victoria. ISBN: 0 642 54469 7.
- HILLMAN, D. (1997). Fatigue and driving – medical aspects. *Paper presented at the Conference on Managing Driver Fatigue*, Perth, Western Australia.
- HULSOF, C. & VAN ZANTEN, V. (1987). Whole-body vibration and low-back pain. *Int. Arch. Occup. Environ. Health*, Vol. 59, pp. 205-220.
- ISO2631-1.2 – (1997). *International Standard. Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration*. International Standards Office, Geneva.
- JOHANNING, E. (1991). Back disorders and health problems among subway train operators exposed to whole-body vibration. *Scand. J. Work. Environ. Health*, Vol. 17, pp. 414-419.
- KAMENSKII, Y. & NOSOVA, I. M. (1989). Effect of whole body vibration on certain indicators of neuro-endocrine processes. *Noise and Vibration Bulletin*, Sept 1989, pp. 205-206.
- KANEKO, T. & JOVANIS, P. P. (1992). Multiday driving patterns and motor carrier accident risk: A disaggregate analysis. *Accident Analysis and Prevention*, Vol 24 (5), pp. 437-456.
- KJELLBERG, A. & WIKSTROM, B. O. (1985). Whole-body vibration: exposure time and acute effects - a review. *Ergonomics*, Vol. 28 (3), pp. 535-544.
- KJELLBERG, A. & WIKSTROM, B. O. (1987). Acute effects of whole-body vibration. *Scand. J Work Environ Health*, Vol. 13, pp. 243-246.
- KJELLBERG, A., WIKSTROM, B. O. & DIMBERG, U. (1985). Whole-body vibration: exposure time and acute effects - experimental assessment of discomfort. *Ergonomics*, Vol. 28 (3), pp. 545-554.
- KNIPLING, R. R. & WIERWILLE, W. W. (1994). Vehicle-based drowsy driver detection: Current status and future prospects. *Proceedings of the IVHS AMERICA Conference. Moving Toward Deployment. Atlanta, Georgia*.
- LANDSTROM, U. & LANDSTROM, R. (1985). Changes in wakefulness during exposure to whole body vibration. *Electroencephal. Clin. Neurophysiol.* Vol 61, pp. 411-415.
- LANDSTROM, U. & LOFSTEDT, P. (1987). Noise, vibration and changes in wakefulness during helicopter flight. *Aviat. Space Environ. Med.* Vol 58, pp. 109-118.
- LAVIE, P. (1986). Ultrashort sleep-waking schedule. III. “Gates” and “forbidden zones” for sleep. *Electroencephalogram Clin. Neurophysiol.* 63: pp. 414-425.
- LISPER, H. O., LAURELL, H. & VAN LOON, J. (1986). Relation between time to falling asleep behind the wheel on a closed track and changes in subsidiary reaction time during prolonged driving on a motorway. *Ergonomics*, Vol 29 (3), pp. 445-453.

- MABBOTT, N. A. & HARTLEY, L. R. (1999). Patterns of stimulant drug use on Western Australian heavy transport routes. *Transportation Research*, Part F (2), pp. 115-130.
- MABBOTT, N. A. & NEWMAN, S. L. (2001). *Safety Improvements in Prescriptive Driving Hours*. AUSTRROADS Report AP-R182, Sydney, New South Wales.
- MACKIE, R. R. & MILLER, J. C. (1978). Effects of hours of service, regularity of schedules and cargo loading on truck and bus driver fatigue. US Department of Transport Report HS 803 799.
- MACKIE, R. R., O'HANLON, J. F. & McCAUNLEY, M. E. (1974). *A Study of Heat, Noise, and Vibration in Relation to Driver Performance and Physiological Status*. California: Human Factors Research Inc. Cited in PETIT, C. & TARRIERE, C. (1992). Synergetic effects of noise, vibration, and heat on driver alertness and performance. *International Federation of Automobile Engineers and Technicians Associations. International Congress*, London, UK.
- MAYCOCK, G. (1995). *Driver Sleepiness as a Factor in Car and HGV Accidents*. TRL Report 169. Transport Research Laboratory, Crowthorne, Berkshire, RG45 6AU. ISSN: 0968-4107.
- McCARTT, A. T., HAMMER, M. C. & FULLER, S. Z. (1998). Research on the scope and nature of fatigued driving among truck drivers in New York State. *VTI Konferens*, No 9A, Part 8, pp. 85-101, Swedish National Road and Transport Institute, Linköping, Sweden.
- McCARTT, A. T., ROHRBAUGH, J. W., HAMMER, M. C. & FULLER, S. Z. (2000). Factors associated with falling asleep at the wheel among long-distance truck drivers. *Accident Analysis and Prevention*, Vol. 32, pp. 493-504.
- McPHEE, B., FOSTER, G. & LONG, A. (2000). *Exposure to Whole Body Vibration for Drivers and Passengers in Mining Vehicles, Part 1 – Findings at four Open-cut Mines and a Coal Loader*. Joint Coal Board Health & Safety Trust, May 2000.
- MISTROT, P., DONATI, P., GALMICHE, J. P. & FLORENTIN, D. (1990). Assessing the discomfort of the whole-body multi-axis vibration: laboratory and field experiments. *Ergonomics*, Vol 33, (12), pp. 1523-1536.
- MITLER, M. M., CARSKADON, M. A., CZEISLER, C. S., DEMENT, W. C., DINGES, D. F. & GRAEBER, R. C. (1988). Catastrophes, sleep and public policy. *Sleep*, Vol. 11 (1), 100-109.
- MOORE-EDE, M., CAMPBELL, S. & BAKER, T. (1988). Falling asleep at the wheel: Research priorities to improve driver alertness and highway safety. In *Proceedings of Federal Highway Administration Symposium on Truck and Bus Driver Fatigue*. Federal Highway Administration, Washington DC.
- PACK, A. I., PACK, A. M., RODGMAN, E., CUCCHIARA, A., DINGES, D. F. & SCHWAB, C. W. (1995). Characteristics of crashes attributed to the driver having fallen asleep. *Accident Analysis and Prevention*, Vol 27 (6), pp. 769-775.
- PADDAN, G. S. ET AL. (1999). *Whole-body vibration: Evaluation of some common sources of exposure in Great Britain*. Health & Safety Executive Books, Contract Research Report 235/1999. ISBN 0-7176-2481-1.

- PELMEAR, P. L., ROOS, J. O. & MAEHLE, W. M. (1992). Occupationally-induced scleroderma. *J. Occup. Med.* January, pp. 20-25.
- PETIT, C. & TARRIERE, C. (1992). Synergetic effects of noise, vibration, and heat on driver alertness and performance. *International Federation of Automobile Engineers and Technicians Associations. International Congress*, London, UK.
- RANDALL, J. M. (1992). Human subjective response to lorry vibration: implications for farm animal transport. *J. Agric. Engng. Res.*, Vol. 52, pp. 295-307.
- RIIHIMAKI, H., TOLA, S., VIDEMAN, T. & HANNINEN, K. (1989). Low-back pain and occupation. A cross-sectional questionnaire study of men in machine operating, dynamic physical work, and sedentary work. *Spine*, Vol. 14, (2), pp. 204-209.
- SEIDEL, H. & HEIDE, R. (1986). Long-term effects of whole-body vibration: a critical survey of the literature. *Int. Arch. Occup. Environ. Health*, Vol. 58, pp. 1-26.
- SEIDEL, H., BLUETHNER, R. & HINZ, B. (1986). Effects of sinusoidal whole-body vibration on the lumbar spine: the stress-strain relationship. *Int. Arch. Occup. Environ. Health*, Vol. 57, pp. 207-223.
- STOOHS, R. A., GUILLEMINAULT, C., ITOI, A. & DEMENT, W. C. (1994) Traffic accidents in commercial long-haul truck drivers: The influence of sleep-disordered breathing and obesity. *Sleep*, Vol. 17, pp. 619-623.
- SWANN, P. (2000). *Heavy Vehicle Driver Health and Sleep Disorders*. Austroads, Sydney, New South Wales.
- SWEATMAN, P. & McFARLANE, S. (2000). *Investigation into the Specification of Heavy Trucks and Consequent Effects on Truck Dynamics and Drivers: Final Report*, FEDERAL OFFICE OF ROAD SAFETY, 2000.
- WICKSTROM, G. (1978). Effect of work on degenerative back disease. *Scand. J. Work. Environ. Health*, Suppl. 1, pp. 1-12.
- WILLIAMSON, A. M., FEYER, A-M., COUMARELOS. C. & JENKINS, T. (1992). *Strategies to Combat Fatigue in the Long Distance Transport Industry. Stage 1: The Industry Perspective*. Report, no CR144. Australian Office of Road Safety (FORS), Canberra, ACT, Australia, ISSN: 0810-770X, ISBN: 0-644-35340-6
- WILLIAMSON, A. M., FEYER, A-M., FRISWELL, R. & LESLIE, D. (1994). *Strategies to Combat Fatigue in the Long Distance Road Transport Industry. Stage 2: Evaluation of Alternative Work Practices*. Federal Office of Road Safety, Report CR 144, Australian Government Publishing Service, Canberra, Australia.
- WILSON, L. J. & HORNER, T. W. (1979). Data Analysis of Tractor-Trailer Drivers to Assess Drivers' Perception of Heavy Duty Truck Ride Quality. Report DOT-HS-805-139, National Technical Information Service, Springfield, VA, USA.
- WYLIE, C. D., SHULTZ, T., MILLER, J. C., MITLER, M. M. & MACKIE, R. R. (1996). *Commercial Motor Vehicle Driver Fatigue and Alertness Study: Project Report*. Report No. FHWA-MC-97-002, Federal Highway Administration, Washington, DC, USA.

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