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# COMPARATIVE STUDY OF WHOLE-BODY VIBRATION EXPOSURE BETWEEN TRAIN AND CAR PASSENGERS: A CASE STUDY IN MALAYSIA

**M.Z. Nuawi[1], A.R. Ismail[2] and N.F. Kamaruddin[1]**

[1]Department of Mechanical and Materials Engineering,
Faculty of Engineering and Built Environment, University Kebangsaan Malaysia,
43600 UKM Bangi, Malaysia;
Phone: +603-89216775, Fax: +603-89259659
E-mail: fanakamaruddin@gmail.com
[2]Faculty of Mechanical Engineering, Universiti Malaysia Pahang,
26300 UMP, Kuantan, Pahang, Malaysia;
Phone: +6012-3456789, Fax: +609-87654321
E-mail: arasdan@gmail.com

## ABSTRACT

Train and car are the important transportations in the whole world. In highly developed countries, train becomes essential for human usage as the most well-known public transportation, whereas car plays a significant role for the human to travel from one place to the other place promptly. High magnitude of vibration formed by the train and car may cause diseases and health problems to the human especially a low back pain. The aim of this study was to evaluate and validate the values of daily exposure to vibration A(8) and vibration dose value (VDV) exposed to the passengers travelling in the train and car and the effects produced by the exposure towards human body, moreover all at once to introduce a newly developed whole-body vibration measurement instrumentation. One national train travelled from East Coast to the South has been chosen to conduct the study. The whole-body vibration exposure was measured in 8 hours, which is equal to the duration for normal occupation condition. One national car has been picked randomly and the exposure was measured in 5 min and 10 min respectively. All the data was computed by using IEPE(ICP$^{TM}$) accelerometer sensor connected to DT9837 device which is capable to measure and analyze vibration effectively. The vibration results attained were displayed in personal computer by using custom graphical user interface (GUI). Matlab software was used to interpret the data obtained. From the results shown, the whole-body vibration exposure level can be determined. It can be concluded that the whole-body vibration absorbed by human body enhanced when the magnitude of vibration exposure experienced by the passengers increased. This can be proved by the increasing of the value of daily exposure to vibration A(8) and VDV calculated in the study.

***Keywords**:* Whole-body vibration, Daily Exposure to Vibration A(8), Vibration dose value, Low back pain, Vibration.

## INTRODUCTION

Ergonomics is the application of scientific principles, methods and data drawn from a variety of disciplines to the development of engineering systems in which people play a significant role. Among the basic disciplines are psychology, cognitive sciences, physiology, biomechanics, applied physical anthropometry, and industrial systems engineering (Kroemer et al., 2003). Matilla (1996) mentioned that the importance of safety and ergonomics had grown significantly. The latest technology had increased the option to broaden the ergonomics and safety features of products and equipment. However, it will also create new risks and the way to manage it would become more complicated. Therefore, it is important for the designer to use ergonomic knowledge in making decision during of machines, equipment, products and systems. There is substantial epidemiologic evidence of associations between physical ergonomics exposures at the workplace, such as lifting, constrained postures, repetitive movements, fast work pace, heavy material manual handling, forceful exertions and vibration, and the occurrence of upper extremity musculoskeletal disorders (Bernard, 1997; Grieco et al., 1998; Hagberg et al., 1995; NRCIM, 2001; van der Windt et al., 2000). To be more specific, ergonomics (also called human factors or human engineering in the United States) defined as the study of human characteristics for the appropriate design of the living and work environment. Its fundamental aim is that all human-made tools, devices, equipment, machines, and environments should advance, directly or indirectly, the safety, well-being, and performance of human beings (Kroemer et al., 2003). Several ergonomic interventions, such as employee training, redesign of process tools or workstations, and improvement of work conditions, were suggested to tackle musculoskeletal problems in industries (Wang et al., 2003; Weestgard and Winkel, 1997).

Various definitions have been given to whole-body vibration (WBV) by dictionaries, companies, and authors themselves. From the Directive 2002/44/EC of the European Parliament and of the Council, the term 'whole-body vibration' means the mechanical vibration that, when transmitted to the whole body, entails risks to the health and safety of workers, in particular lower-back morbidity and trauma of the spine (Directive 2002/44/EC). WBV is defined as vibration occurring when a greater part of the body weight is supported on a vibrating surface. WBV principally occurs in vehicles and wheeled working machines. In most cases exposure to WBV occurs in a sitting position and the vibration is then primarily transmitted through the seat pan, but also through the back rest. WBV may impair performance and comfort. It has also been claimed to contribute to the development of various injuries and disorders. In many work situations WBV is therefore an evident and annoying occupational health problem (Griffin et al., 1990).

Low back pain (LBP) is among the most common and costly health problems (Garg and Moore, 1992; Van Tulder et al., 1995). Occupational, non-occupational, and individual risk factors play a role in the development, the duration, and the recurrence of LBP. Several critical reviews have discussed the evidence on occupational risk factors for back disorders (Burdorf and Sorock, 1997; Bovenzi and Hulshof, 1999; Lings and Leboeuf-Yde, 2000; Waddell and Burton, 2000). All these reviews conclude that there is strong epidemiological evidence for a relation between occupational exposure to WBV and LBP. In five European countries (Belgium, Germany, Netherlands, France, Denmark), LBP and spinal disorders due to WBV are currently recognized as an occupational disease (Hulshof et al., 2002). However, high exposures and adverse effects still occur as WBV is a common occupational risk factor for LBP, affecting 4% to 8% of the workforce in industrialized countries (Palmer et al., 2000). Important high risk groups are drivers of off-road vehicles (for example, earth moving, forestry, and agricultural machines), drivers of forklift trucks, lorries, or buses, crane operators, and helicopter pilots.

## EXPERIMENTAL DESIGN

Whole-body vibration measurement was done according to ISO 2631-1:1997. The triaxial accelerometer sensor was located between the train and car's passenger contact points with the vibration source. Then the passenger sat on the accelerometer, for example as shown in Figure 1.

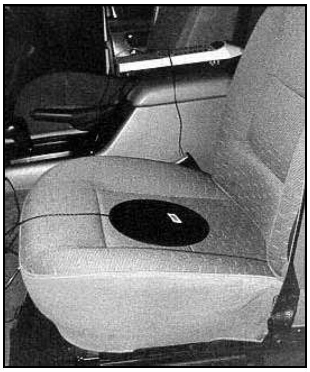


Figure 1: Triaxial accelerometer sensor used for WBV measurement

There were two devices used in the study which were IEPE(ICP$^{TM}$) accelerometer sensor, and DT9837 instrument. Based on Figure 2, the IEPE(ICP$^{TM}$) accelerometer sensor (also known as triaxial seat accelerometer) been used in this study was DYTRAN Model 5313A. The sensor was utilized to assess the vibration level. The accelerometer consists of a piezoelectric element connected to a known mass. When the accelerometer is vibrated, the mass applies force to the piezoelectric element, generating an electrical charge that is proportional to the applied force. Then this charge was deliberated to determine the vibration characteristics. Most accelerometers require a current source of 4 mA and a compliance voltage of at least 18V to drive their internal circuitry. Other accelerometers require a 2 mA current source, but have limitations in cable length and bandwidth. The DT9837 instrument was a highly accurate five channel data acquisition module that is ideal for portable noise and vibration measurements. It has 4 simultaneous, 24-bit A/D channels for high resolution measurements. This instrument supports for four IEPE inputs, including 4 mA current sources. Portable operation can be done by the DT9837 because no external power supply needed and runs on USB power. The DT9837 has tachometer input support in the A/D data stream for synchronizing measurements. Sampling rate of over 52 KHz was produced by this instrument. It has low frequency measurements supported with a wide pass band of 0.5 Hz to 25.8 KHz (0.49 x sampling frequency). The DT9837 was a programmable trigger for analog input operations for maximum flexibility. Figure 3 and Figure 4 showed the DT9837 model and the summary features of the instrument.

In this study, Matlab software was applied to analyze the vibration signal gathered by DT9837 instrument from USB port. The Matlab GUI scripts have been examined by using GUIDE function for ease measurement and assessment of WBV exposure. From this Matlab script, three graphs of each axes been meditated for current analysis. Besides, the data and vibration signal can be saved in the personal computer for next analysis. Thus, the total of daily exposure to vibration towards human can be evaluated through the accelerometer sensor, DT9837 instrument and this Matlab software.

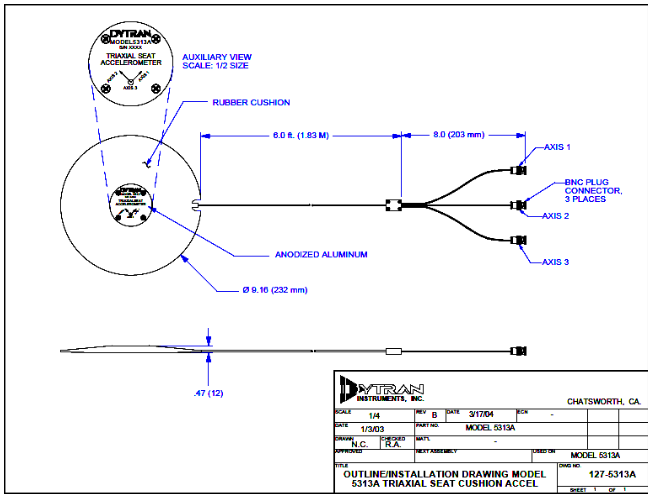
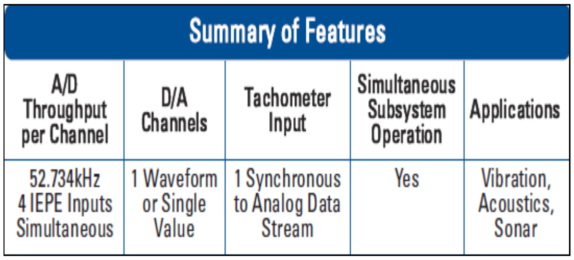


Figure 2: Triaxial seat accelerometer (DYTRAN model 5313A)

Figure 3: DT9837 model



| Summary of Features | | | | |
|---|---|---|---|---|
| A/D Throughput per Channel | D/A Channels | Tachometer Input | Simultaneous Subsystem Operation | Applications |
| 52.734kHz<br>4 IEPE Inputs Simultaneous | 1 Waveform or Single Value | 1 Synchronous to Analog Data Stream | Yes | Vibration, Acoustics, Sonar |

Figure 4: Summary features of DT9837

Matlab was a well known interactive software environment for data acquisition and analysis, report generation, and test system development. It provides a complete set of tools for acquiring and analyzing analog and digital input output signals from a variety of PC-compatible data acquisition hardware. The Matlab Data Acquisition

Toolbox configured the external hardware devices, read data into Matlab and Simulink for immediate analysis, and send out data for controlling the system. The diagram shown in Figure 5 depicts an example using Matlab and the Matlab Data Acquisition Toolbox with Data Translation's DT9837 to acquire vibration data from USB modules. Notice that the Data Translation provides an interface layer, called the DAQ adaptor for Matlab, which allows the Matlab Data Acquisition Toolbox to communicate with Data Translation's hardware, while the Data Acquisition Toolbox is collecting data, Matlab can analyze and visualize the data.

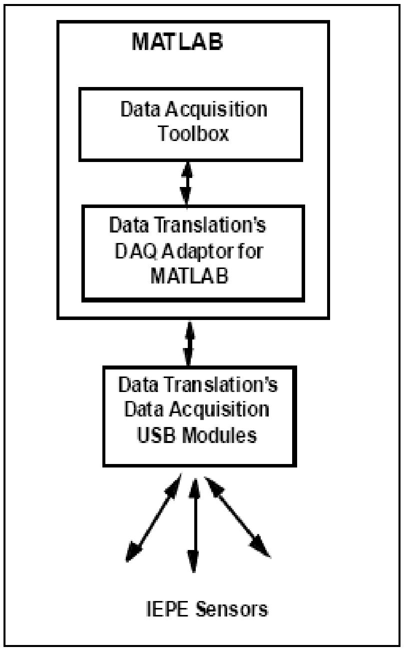


Figure 5: Flow chart of data acquisition process

Excessive exposure of whole-body vibration usually occurred at working area which involved long duration of exposure and high-level of vibration magnitude. Train is one of the most public transportations that produced high magnitude of vibration. While the road surface circumstance is one of the environmental factors that may contribute to high-level of vibration magnitude. In this study, the assessment of whole-body vibration was completed by deciding number of sampling rate to 1000 samples per second. Compution of the exposure time was set to 8 hours for each experiments, which equal to the duration for normal occupation stipulation. After the accelerometer and DT9837 instrument were connected, the process of collecting the data acquisition of the train vibration was started. The total vibration of each axes which were x, y, and z-axis felt by the passenger was displayed in a plotted graph by using Matlab software. One national train travelled from East Coast to the South has been chosen to conduct the study. The study has been conducted at different locations. The location of measurement for each experiments was explained in Table 1. Whole-body vibration measurement explored by the passenger was done three times at different train trip areas. Among the areas passing by the train were namely from Kajang to Seremban, from Seremban to Gemas, and from Segamat to Tampin.

Table 1: Location of Measurement

| Experiment | Location |
|---|---|
| 1 | From Kajang to Seremban |
| 2 | From Seremban to Gemas |
| 3 | From Segamat to Tampin |

Road surface circumstance is a big dominant parameter towards whole-body vibration especially at low frequency. One national car has been chosen to conduct the study. The car passenger was picked up randomly without consider the individual characteristics of the passenger. In this study, whole-body vibration measurement was done by changing the road condition passed by the car. Compution of the exposure time were set to 5min and 10 min respectively. The study has been conducted at different locations with different road conditions. The road circumstances for each experiments was explained in Table 2. Whole-body vibration measurement explored by the car passenger was done three times at three different road conditions. Among the road passing by the car were uneven and zigzag road, even and zigzag road, and lastly even and straight road.

Table 2: Road Circumstances

| Experiment | Measurement Time (min) | Road Condition |
|---|---|---|
| 1 | 5 | Uneven and zigzag road |
| 2 | 10 | Even and zigzag road |
| 3 | 10 | Even and straight road |

## RESULTS AND DISCUSSION

From the experiments done, daily exposure to vibration A(8) value, VDV and exposure points value were evaluated by using formula (1), (2), and (3). But, by employed the Matlab GUI, the calculation of those values was done by choosing the analysis method from the organize Matlab menu. When the option been made followed the passenger's need, the calculated values completed by connect the update button. Hence, the results were displayed in the custom made GUI.

Daily exposure to vibration A(8) is expressed as Eq. (1).

$$A(8) = \text{Vibration value}\left(\frac{\text{m}}{\text{s}^2}\right) \times \sqrt{\frac{\text{Exposure time (min)}}{480\,\text{(min)}}} \tag{1}$$

Vibration dose value (VDV) is expressed as Eq. (2).

$$VDV = \left(\int_0^{\text{T}} a^4(t)dt\right)^{0.25} \tag{2}$$

where $a(t)$ = frequency-weighted acceleration (m/s$^2$)

$T$ = the total period of the day during which vibration may occur (s)

Exposure points value can be expressed as Eq. (3).

$$Exposure\ points = 2 \times (\text{Vibration value})^2 \tag{3}$$

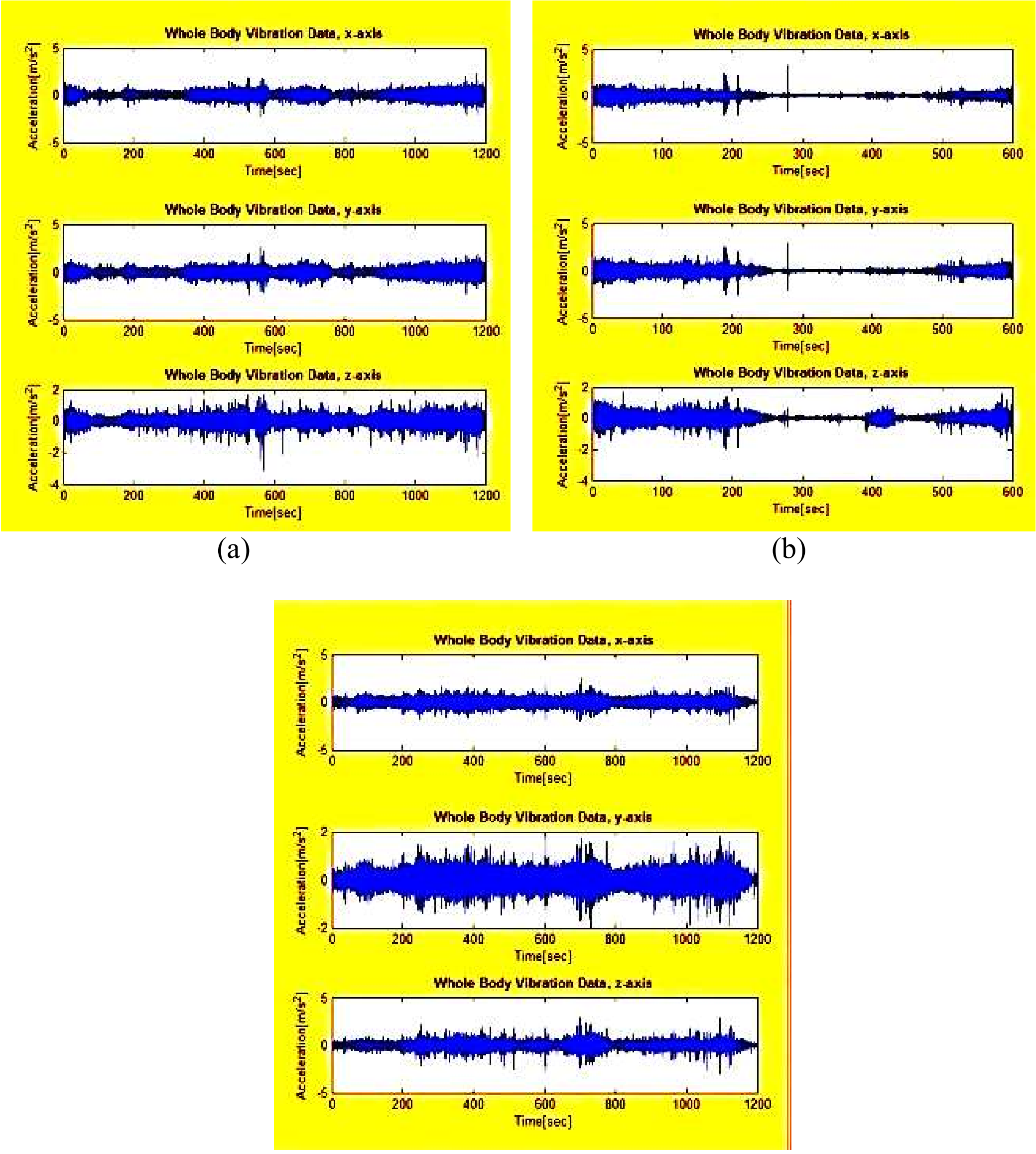
All the data obtained in the train was organized in Table 3. Whole-body vibration graphs were demonstrated in Figure 6. For Figure 6(a), the graph of whole-body vibration was collected namely from Kajang to Seremban, while Figure 6(b) was from Seremban to Gemas, and Figure 6(c) from Segamat to Tampin. Figure 7 shows the calculation of exposure points system and the vibration dose value.

Table 3: Whole-body vibration measurement data collected in train

| **Analysis Method** | **Experiment 1**<br>**From Kajang To Seremban** | **Experiment 2**<br>**From Seremban To Gemas** | **Experiment 3**<br>**From Segamat To Tampin** |
|---|---|---|---|
| Daily exposure to vibration A(8) | 0.3221 m/s$^2$ | 0.2884 m/s$^2$ | 0.3749 m/s$^2$ |
| Exposure points system | 41.4867 point | 33.2716 point | 56.206 point |
| Vibration dose value (VDV) | 1.1014 m/s$^{1.75}$ | 1.0973 m/s$^{1.75}$ | 1.2513 m/s$^{1.75}$ |
| Daily exposure action value time (0.5 m/s$^2$) | 9 hours 50 min | 12 hours 16 min | 7 hours 16 min |
| Daily exposure limit value time (1.15 m/s$^2$) | 52 hour 3 min | 64 hour 54 min | 38 hour 25 min |
| Points per hour | 5.1858 point | 4.159 point | 7.0258 point |
| Time achieving 1.75 m/s$^{1.75}$ | 1 hour 29 min | 1 hour 30 min | 53 min |

The results of this study indicated that in experiment 3, the values of daily exposure to vibration A(8) and VDV were much higher than the other two experiments. The values of daily exposure to vibration A(8) and VDV were 0.3749 m/s$^2$ and 1.2513 m/s$^{1.75}$ respectively. It seems possible that these results were due to indelicate track passed by the train, the train operation style, and speed differences compared to experiment 1 and 2. In addition, the daily exposure action value time only required 7 hours 16 min to meet the standardized value of 0.5 m/s$^2$ to an eight hour reference period. Surprisingly, this result was found to exceed the standard time of whole-body vibration assessment which was 8 hours stated in ISO 2631-1:1997. The reason for this is not clear but it may have something to do with the speed of the train that generated high magnitude of vibration value to the train. The high magnitude of whole-body vibration exposure produced by the train may contribute to musculoskeletal disorders to the passengers. In reviewing the literature, there was found the relation between occupational vehicles and whole-body vibration exposure that lead to musculoskeletal disorders.

In the car study, three different road surface conditions have been passed through for whole-body vibration assessment occurred in the car. The first road type was uneven and zigzag road at Golf Kajang. The second condition was even and zigzag road which at Universiti Kebangsaan Malaysia (UKM) areas. While the third road was at Bandar Baru Bangi areas which even and straight road. The speed of the car during the study was set to 40km/h. All the data obtained in the experiment were organized in Table 4. Whole-body vibration graphs were demonstrated in Figure 8. For Figure 8(a), the graph of whole-body vibration was collected at uneven and zigzag road, while Figure 8(b) was at even and zigzag road, and Figure 8(c) was even and straight road.



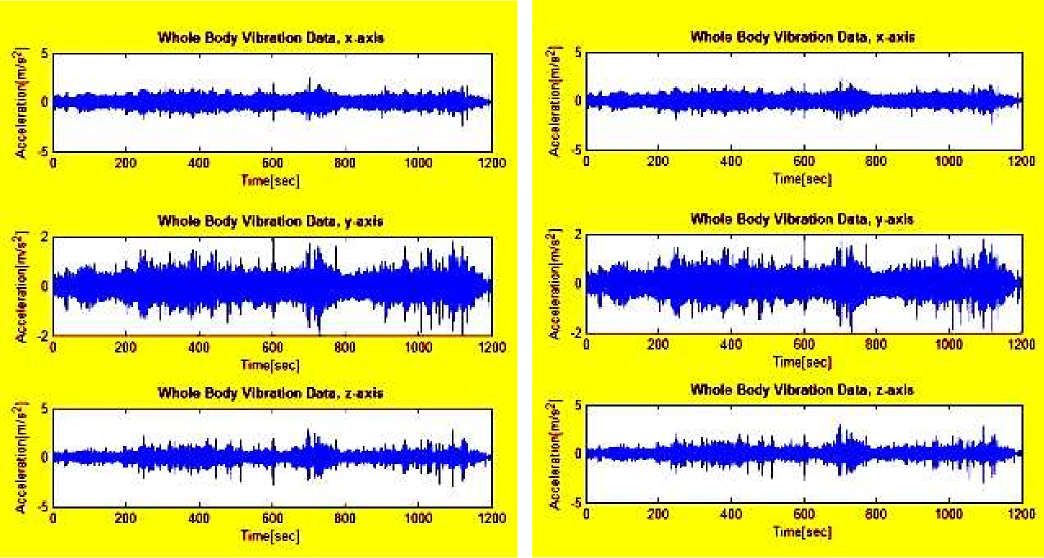
(a)

(b)

(c)

Figure 6: Whole-body vibration custom data acquisition system (a) from Kajang to Seremban, (b) from Seremban to Gemas, and (c) from Segamat to Tampin

Whole-body vibration risks towards human's health enhanced when the amplitude of the vibration signal absorbed by the human body increased. This situation has been proved by the comparison of the three experiments done in the study. In the first experiment, the uneven and zigzag road surface had boost up the vibration amplitude. Thus, the daily exposure to vibration A(8) and the VDV absorbed by the passenger was higher compared to experiment 2 and experiment 3 eventhough the measurement time only took 5 min. At the same time, exposure whole-body vibration points system value in experiment 1 was high too. In other words, daily exposure action value time (0.5 m/s$^2$) and daily exposure limit value time (1.15 m/s$^2$) were at low level than in experiment 2 and 3. From the results attained, the frequency weighted acceleration value indicated in the study was closely to the permissible value of exposure limit stated according to ISO 2631-1:1997. Therefore, the high magnitude of WBV may cause musculoskeletal disorders to the train and car passengers.

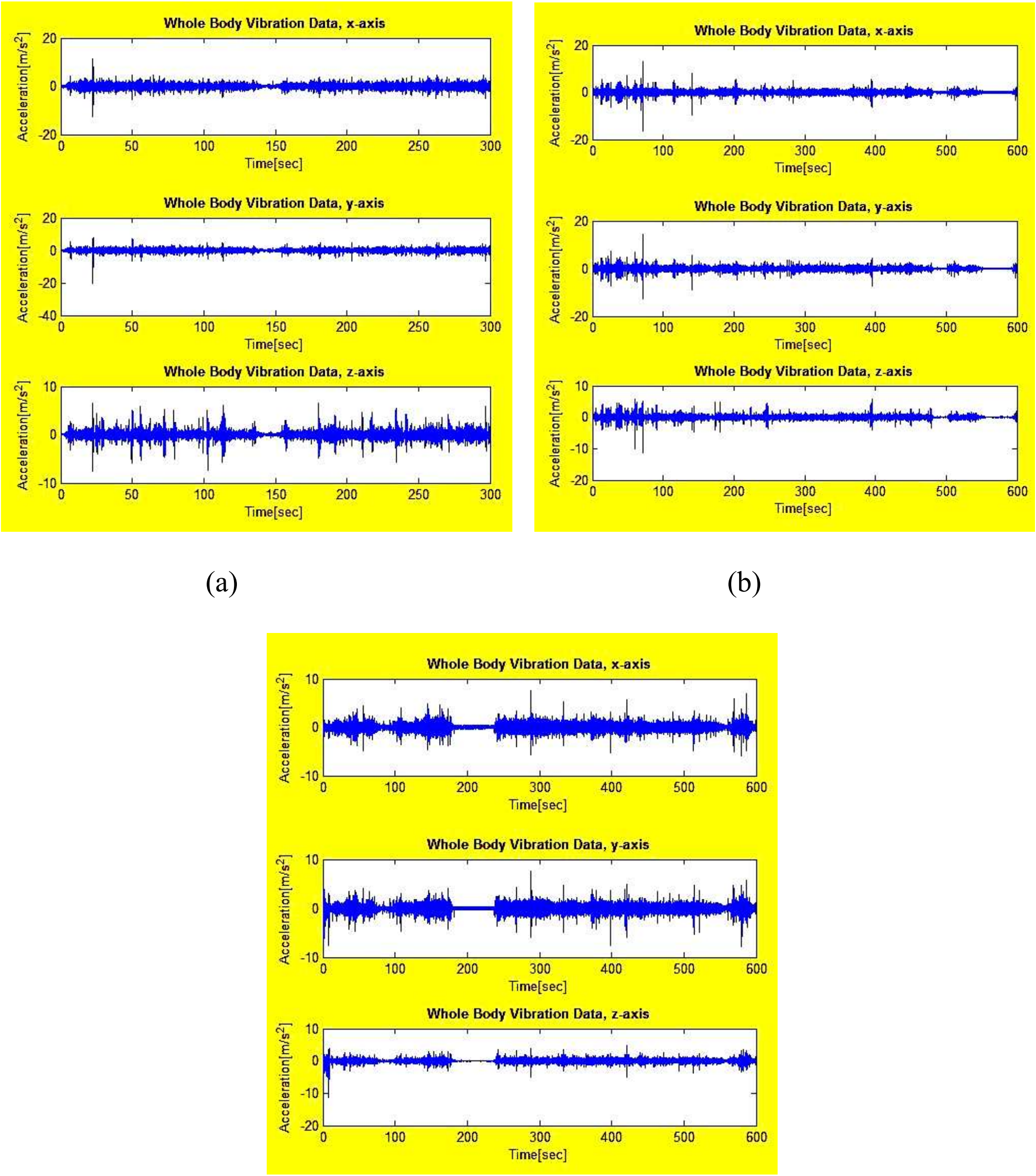


(a) (b)

Figure 7: (a) Exposure points system; (b) Vibration dose value calculation

Table 4: Whole-body vibration measurement data collected in car

| **Analysis Method** | **Experiment 1 (5 min) Uneven and Zigzag Road** | **Experiment 2 (10 min) Even and Zigzag Road** | **Experiment 3 (10 min) Even and Straight Road** |
|---|---|---|---|
| Daily exposure to vibration A(8) | 1.0782 m/s$^2$ | 0.8097 m/s$^2$ | 0.7928 m/s$^2$ |
| Exposure points system | 464.96 point | 262.219 point | 251.381 point |
| Vibration dose value (VDV) | 6.3314 m/s$^{1.75}$ | 4.3958 m/s$^{1.75}$ | 3.7264 m/s$^{1.75}$ |
| Daily exposure action value time (0.5 m/s$^2$) | 53 min | 1 hour 33 min | 1 hour 37 min |
| Daily exposure limit value time (1.15 m/s$^2$) | 4 hours 39 min | 8 hours 14 min | 8 hours 35 min |
| Points per hour | 58.1201 | 32.7773 | 31.4226 |
| Time achieving 1.75 m/s$^{1.75}$ | 13 hour 32 min | 58 hour 14 min | 112 hour 45 min |



(a)

(b)

(c)

Figure 8: Whole-body vibration custom data acquisition system (a) Uneven and zigzag road, (b) Even and zigzag road, and (c) Even and straight road

The basic method (frequency weighted r.m.s. method) in ISO 2631-1 is primarily applicable to assessment of health risks from stationary vibrations not containing severe multiple or single event shocks. Single event shocks can be analyzed with the additional method running r.m.s. in 2631-1, although there is no information on health risk levels. The additional method VDV (frequency weighted fourth power vibration dose value) is more sensitive to shocks than the basic method, but it will still underestimate the health risk of vibration containing severe shocks in comparison to the health risk of vibration not containing severe shocks. The EU Physical Agents Directive uses the basic method for assessment of health risk with VDV as an alternative. The two methods give different assessment results·

The root-mean-square (r.m.s) vibration magnitude is expressed in terms of the frequency weighted acceleration at the seat of a seated person or the feet of a standing person, it is expressed in units of meters per second squared (m/s²). The r.m.s vibration magnitude represents the average acceleration over a measurement period. It is the highest of three orthogonal axes values ($1.4a_{wx}$, $1.4a_{wy}$ or $a_{wz}$) that are used for the exposure assessment. For knowledge, the frequency weighted acceleration value which less than 0.45m/s$^2$ showed that there was no negative health effect expected. Whilst the frequency weighted value in between 0.45m/s$^2$ and 0.90m/s$^2$ explained that the negative health effects still can be accepted. But, the frequency weighted acceleration value greater than 0.90m/s$^2$, high risks of bad health problems were anticipated. The data from Table 5 indicated the r.m.s acceleration value for exposure limit in 8 hours. The passengers exposed to the whole-body vibration exposure must not exceed this standard value. Otherwise, the passengers may have an experience of bad health problems.

Table 5: Standard Value of RMS Acceleration

| **Exposure Limit** | **8 hrs** | **4 hrs** | **2.5 hrs** | **1 hr** | **30 min** | **5 min** | **1 min** |
|---|---|---|---|---|---|---|---|
| **RMS acceleration** | 2.8 m/s$^2$ | 4.0 m/s$^2$ | 5.6 m/s$^2$ | 11.2 m/s$^2$ | 16.8 m/s$^2$ | 27.4 m/s$^2$ | 61.3 m/s$^2$ |

The high magnitude of whole-body vibration exposure produced by the train and car may contribute to musculoskeletal disorders to the passengers. In reviewing the literature, there was found the relation between occupational vehicles and whole-body vibration exposure that lead to musculoskeletal disorders. The term musculoskeletal disorder refers to conditions that involve the nerves, tendons, muscles, and supporting structures of the body (Bernard, 1998). Exposure to WBV is another occupational risk factor that may cause LBP in participants of occupational vehicles (Bovenzi and Hulshof, 1999). In western countries an estimated 4–7 percent of all employees are exposed to potentially harmful WBV. Experimental studies have found that resonance frequencies of most of the organs or other parts of the body lie between 1 and 10 Hz, which are in the range of frequencies found in occupational machines and vehicles. Six million workers are exposed to WBV typically while in a seated position including delivery vehicles drivers, forklift operators, helicopters pilots, and construction equipment operators (Griffin, 2006). Tractor drivers have reported 61–94% prevalence of LBP and pathological changes in the spine, and heavy-equipment drivers report 70% prevalence of LBP. WBV is recognized as an important risk factor for occupational LBP in a variety of occupational groups (Joubert and London, 2007). At least four European countries have placed WBV injury on their scheduled lists of occupational diseases (Hulshof et al., 2002). Among such physical exposures encountered in working conditions, WBV has repeatedly been identified as a risk factor for LBP (Santos et al., 2008). Several epidemiologic studies conducted in the past several years found strong evidence for a correlation between exposure to WBV and the occurrence of LBP (Noorloos et al., 2008). The NRCIM (2001) reported that there is evidence of a ‘‘clear relationship between back disorders and whole-body vibration”. Joubert and London (2007) had determined the association between back belt usage and back pain amongst forklift drivers exposed to WBV. LBP has been identified as one of the most costly disorders among the worldwide working population and sitting has been associated with risk of developing LBP (Lis et al., 2007). It was showed that sustaining trunk sitting postures corresponding to mining vehicle operators generates back muscle fatigue and postural balance (Santos et al., 2008). On the other hand, Noorloos et al. (2008) had been concluded that occupational participants exposed to WBV, with a high BMI do not have an increased risk for the development of LBP, so the focus should be on other factors.

## CONCLUSION

WBV gained by human body increased when the magnitude of the vibration experienced by the passengers enlarged. This phenomena can be proved by the increasing of daily of exposure to vibration A(8) value and vibration dose value (VDV). Hence, it was clearly explained that most of the train and car passengers were exposed to worse WBV during their travelling time because the frequency-weighted acceleration value indicated in the study was closely to the value of exposure limit value according to ISO 2631-1:1997. Consequently, this condition may cause health problems to the passengers. Empirical studies showed that there was a relation between an occupational vehicles and whole-body vibration that lead to musculoskeletal disorders. But, from the scenario of Malaysian population, there is insufficient research on this problem. Because of insufficient knowledge of diseases affected by WBV, the passengers find difficulty to know exactly the exposure of WBV to them and how much they have been exposed. As a conclusion, more studies are needed to provide clear evidence of the association between WBV and musculoskeletal disorders especially on Malaysian occupational vehicles. A further study with more focus on the drivers of the train, car, and heavy vehicle are therefore suggested.

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## Nomenclature

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|---|---|
| Hz | Hertz |
| KHz | kilo Hertz ($10^3$) |
| Km/h | kilometer per hour |
| m | meter ($10^2$) |
| mA | mili Ampere ($10^{-3}$) |
| min | minute |
| s | second |
| V | voltage |