DEVELOPMENT OF NOISE AND VIBRATION EXPOSURE MONITORING SYSTEM FOR MALAYSIAN ARMY (MA) THREE-TONNE TRUCKS

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Graphical abstract

Noise measurement

All data were transferred to laptop
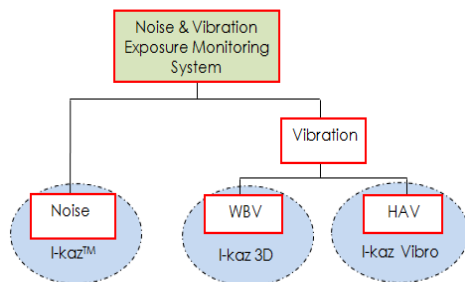
WBV measurement

HAV measurement

Abstract

Exposure to noise and vibration in the driver's cabin of Malaysian Army (MA) three-tonne trucks can cause discomfort to the drivers and passengers, and can be classified as hazardous if exposed to more than the standard 8 h time period. This study was conducted for two different road conditions often used by MA vehicles; tarmac and dirt roads. Noise exposure was measured using a DuO sound level meter, which is capable of recording raw sound pressure in Pa. Whole-body vibration (WBV) and hand-arm vibration (HAV) were measured using a Brüel&Kjær Type 3649 vibration analyser, which is capable to record WBV and HAV raw data from the driver's seat and steering wheel. All the raw data was analysed using the Integrated Kurtosis-Based Algorithm for Z-Notch Filter (I-kaz™). Depending on the type of signal, an exposure model was developed for each measured parameter, with I-kaz™ used for noise, I-kaz 3D for WBV and I-kaz Vibro for HAV. With reference to the limits from the respective international standards, a noise and vibration monitoring system for MA three-tonne trucks was then developed.

Keywords: Noise; whole–body vibration WBV); hand-arm vibration (HAV); Malaysian Army (MA) three-tonne trucks; Integrated Kurtosis-Based Algorithm for Z-Notch Filter; exposure monitoring system

Abstrak

Pendedahan kepada hingar dan getaran dalam kabin pemanduan trak tiga-tan Tentera Darat (TD) Malaysia boleh menyebabkan ketidakselesaan kepada pemandu dan penumpang, dan boleh dikelaskan sebagai berbahaya jika terdedah kepada tempoh masa yang standard iaitu lebih daripada 8 jam. Kajian ini dijalankan pada dua permukaan jalan yang berbeza dan sering digunakan oleh kenderaan TD iaitu jalan berturap dan jalan tanah merah. Pendedahan hingar diukur dengan menggunakan meter paras bunyi Duo, yang mampu merekodkan tekanan bunyi dalam unit Pa. Getaran seluruh-badan (WBV) dan getaran tangan-lengan (HAV) pula diukur

dengan menggunakan penganalisis getaran Brüel & Kjær Jenis 3649, yang mampu untuk merakam data mentah WBV dan HAV dari tempat duduk pemandu dan stereng. Semua data mentah dianalisis menggunakan Algoritma Bersepadu Berasaskan Kurtosis Bagi Penapis Z-Notch (I-kaz™). Bergantung kepada jenis isyarat yang diukur, model pendedahan telah dibangunkan bagi setiap parameter iaitu I-kaz™ digunakan untuk hingar, I-kaz 3D untuk WBV dan I-kaz Vibro untuk HAV. Dengan merujuk kepada had dari piawaian antarabangsa masing-masing, satu sistem pemantauan hingar dan getaran untuk trak tiga-tan TD dapat dibangunkan.

Kata kunci: Hingar; getaran seluruh-badan; getaran lengan-tangan; trak 3-tan Tentera Darat (TD) Malaysia; algoritma bersepadu berasaskan kurtosis bagi penapis z-Notch; I-kaz 3D; I-kaz Vibro

1.0 INTRODUCTION

Vehicle drivers experience discomfort due to exposure to noise and vibrations from the movement of vehicles. Drivers are exposed to vibration from contact with the surface of the driver seat and vibrating steering wheel [1], and to noise generated by vehicles such as from engine, exhaust, tires and environment noise [2]. Exposure to excessive noise will cause risk to health, communication, negative effects during sleep, fatigue and deterioration of job performance [2], while discomfort from vibration will cause fatigue and lethargy, and health disorders. This effect is proportional to the period of vehicle driving [3]. Drivers who drive for a long period will feel more tired and lethargic as compared to driving for short periods of time.

The noise and vibration exposure that is closest to the driver are cabin noise, and vibration received directly from the seating (whole-body vibration (WBV)) and steering wheel (hand-arm vibration (HAV)) [3, 4, 5]. Vibration causes excitation of the chassis structure, which is transmitted via mechanical vibrations into the driver's compartment, where it can be felt as vehicle interior vibrations in the seat, steering wheel, and/or body floor [6]. All of these noise, vibration, and harshness (NVH) parameters have an adverse impact on work performance and health of vehicle drivers [6, 7]. Thus, in this paper, these parameters are selected to study aspects of noise and vibration exposure experienced by Malaysian Army (MA) drivers. The study of noise exposure is based on the international standards of the Occupational Safety and Health Administration (OSHA) and Occupational Safety and Health Act 1994. The study of WBV and HAV exposure is guided by the international standards of ISO 2631-1(1997), BS 6841 (1987) and Directive 2002/44/EC (2002).

This paper is aimed at developing a noise and vibration exposure monitoring system using a new statistical-based approach known as Integrated Kurtosis-Based Algorithm for Z-Notch Filter (I-kaz™). I-kaz™ was chosen because previous studies show it's proven in analyzing various signals such as machining, regular vibration monitoring, ultrasound signals, noise measurement and ergonomics [11–16]. The noise and vibration exposure model proposed for this study consists of a combination of three exposure models for noise, WBV and HAV, which will be developed using I-kaz™ [18], I-kaz 3D [16] and I-kaz Vibro [17] respectively (Figure 1). All three models will facilitate the determination of exposure to noise and vibration to the driver and warning will be given to the driver if the noise and vibration exceeds the limit set by the existing standards.
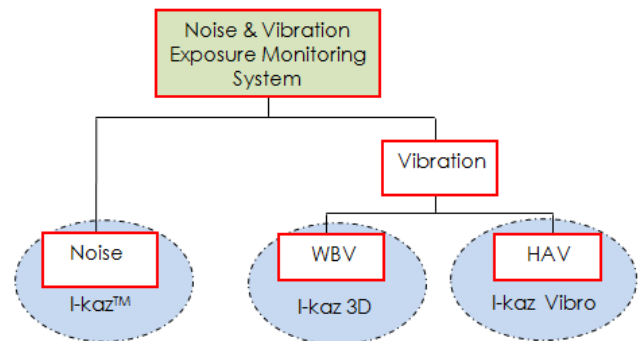

Figure 1 Several I-kaz™ methods were been used in this study.

2.0 INTEGRATED KURTOSIS-BASED ALGORITHM FOR Z-NOTCH FILTER(I-KAZ™)

The sampling theorem states that perfect signal analysis is possible when the sampling frequency f_s is greater than twice the maximum frequency f_{max} of the sampled signal. In I-kaz™, the time domain signal is decomposed into three frequency ranges, which are x-axis for low frequency (LF) range of 0-0.25 f_{max}, y-axis for high frequency (HF) range of 0.25-0.5 f_{max}, and z-axis for very high frequency (VF) range of higher than 0.5 f_{max}. The selection of 0.25 f_{max} and 0.5 f_{max} as the low and high frequency limits respectively imply the concept of 2nd order Daubechies in the signal decomposition process [11, 14, 15]. I-kaz™ can be written in terms of kurtosis K and standard deviation σ as follows:

$$Z^\infty = \frac{1}{n}\sqrt{K_x\sigma_x^{\,4} + K_y\sigma_y^{\,4} + K_z\sigma_z^{\,4}} \qquad (1)$$

where n is the number of data points, K_x, K_y and K_z, and σ_x, σ_y and σ_z are the kurtosis and standard deviation values of each axis respectively.

I-kaz 3D can be written in the following equation:

$$Z_{3D}^{\infty} = \frac{1}{n}\sqrt{K_I\sigma_I^4 + K_{II}\sigma_{II}^4 + K_{III}\sigma_{III}^4} \qquad (2)$$

where K_I, K_{II}, and K_{III}, and σ_I, σ_{II} and σ_{III} are the kurtosis and standard deviation of signals in the x-, y- and z-axes respectively [16].

I-kaz Vibro equation to compute Z_v^{∞} can be written in terms of K and σ as in the following equation:

$$Z_v^{\infty} = \frac{1}{n}\sqrt{K_A\sigma_A^4 + K_V\sigma_V^4 + K_D\sigma_D^4}, \qquad (3)$$

where K_A and σ_A are the kurtosis and standard deviation, respectively, for acceleration in the x-axis, K_V and σ_V are the kurtosis and standard deviation, respectively, for velocity in the y-axis, and K_D and σ_D are the kurtosis and standard deviation, respectively, for displacement in the z-axis [17].

3.0 METHODOLOGY

Noise in a MA three-tonne truck's driving compartment was measured using a DuO smart noise monitor, with its calibration performed using a Brüel&Kjær4231 calibrator before and after the measurements. The recording for duration of 180 s intervals contained 9,000 samples of instantaneous sound pressure raw data. The sampling period, which is the time difference between two consecutive samples, is 1/50 Hz = 0.02 s [13]. In addition to the evaluation of sound pressure data, the A-weighted equivalent SPL L_{Aeq} was measured to determine the permissible exposure time for each truck speed. L_{Aeq} and sound pressure p are related by the following equation:

$$L_{A_{eq}} = 20 \log_{10}\frac{p}{p_{ref}} \qquad (4)$$

where p_{ref} is the reference sound pressure value and equals to 20×10^{-6} Pa [13].

The guidelines for the measurement and evaluation of human exposure to vibration are defined by ISO 2631-1 (1997) for WBV measurement and ISO 5349-1 (2001) for HAV measurement. These standards provide guidance on the quantification of WBV and HAV in relation to human health and comfort. The frequency range that is most often associated with WBV is approximately 1 to 80 Hz [16]. HAV acceleration was measured in the tangential direction relative to the steering wheel. The time histories of acceleration values were obtained from one-third octave band analysis in the frequency range of up to 100 Hz, which is the frequency range of vibration in MA three-tonne truck steering wheels [17]. A Brüel&Kjær Type 3649 five-

channel vibration analyser was used as the data acquisition system, which logged 800 times/s in each axis in unit of ms^{-2}, to record WBV and HAV exposures from the driver seat and steering wheel (Figure 2).
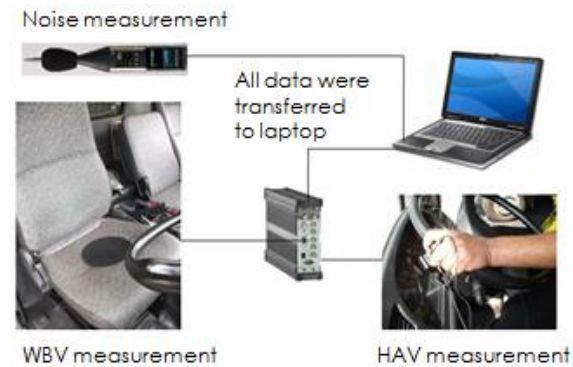

Figure 2 Experimental setup for measurement of noise, WBV and HAV exposure.

The accelerometer measured WBV in the x- (fore-to-aft), y- (left-to-right side) and z- (buttocks-to-head) axes. The MA drivers sat on the triaxial seat accelerometer that was aligned on the seat. Raw, unweighted tri-axial WBV measurements were collected using a seat pad containing a Brüel&Kjær Type 4524 tri-axial piezoelectric accelerometer mounted on the driver's seat, while a single-axis Brüel&Kjær piezoelectric accelerometer was placed on the top left side of the steering wheel. As shown in Figure 2, all the collected data was stored in the portable laptop. The data was processed using MATLAB and Microsoft Excel to analyse the WBV and floor vibration from each run. Accelerometer calibrations were conducted prior to all data collection sessions using a Bruel&Kjaer Calibration Exciter Type 4294 with oscillation frequency of 159.2 Hz and acceleration level of 10 ms^{-2} (RMS) [16]. The tangential direction acceleration time histories were measured under different conditions: idle, moving at speeds of 20, 40, 60 and 80 kmh^{-1} on a tarmac road, and moving at speeds of 10, 20, and 30 kmh^{-1} on a dirt road [17].

The selection of different road surfaces was because the interaction between the truck tyres and road surface gives major effect to the generated hand and vibration exposure on the truck driver [16]. The tarmac road has a flat, smooth surface and occasional unevenness, which results in minimum disturbances. The dirt road is an unpaved road made from subgrade materials and has frequent random irregularities that produces excessive casual vibrations [13].

Measured vibration dose value (VDV_{meas}) was developed in response to experimental researches that showed the effectiveness of using the fourth power instead of the second power in RMS averaging [16]. Mathematically, VDV_{meas} can be expressed as:

$$VDV_{meas} = \sqrt[4]{\int_0^T a_w^4(t)dt} \qquad (5)$$

VDV(8) is the *VDV* measured over the elapsed time, which is extrapolated / interpolated to the value that the same signal would have been given if the elapsed time was 8 h and multiplied by the corresponding *k*-factor or scaling factors [20]. *VDV* exposure (*VDV_exp*) of the each axis, can be calculated using the following formula:

$$VDV_{exp} = VDV_{measure} * k \left(\frac{T_{exp}}{T_{meas}}\right)^{\frac{1}{4}} \tag{6}$$

where *T_meas* is the measurement period and *T_exp* is the expected full exposure time equivalent in 8 h. The highest value between *VDV_exp,x*, *VDV_exp,y* and *VDV_exp,z* is the 8-h equivalent for *VDV(8)* [16]:

$$VDV\,(8) = \max\{\,VDV_{exp,\,x},\ VDV_{exp,\,y},\ VDV_{exp,\,z}\,\} \tag{7}$$

For HAV, the daily vibration exposure *A(8)* is derived as the total vibration value from the RMS frequency weighted acceleration (*a_hwz*). The daily vibration exposure in terms of the 8-h energy equivalent was derived from the magnitude of the vibration (vibration total value) and daily exposure duration. In order to facilitate comparisons between daily exposures of different durations, the daily vibration exposure was expressed in terms of the 8-h energy equivalent frequency-weighted vibration total value, as shown in the following equation:

$$A(8) = a_{hwz}\sqrt{\frac{T}{T_0}} \tag{8}$$

Where *T* is the total daily duration of exposure in s to the exposure *a_hwz* and *T_o* is the reference duration of 8 h (28,800 s).

4.0 RESULTS AND DISCUSSION

For noise, the curve fit method with linear polynomial regression was used to plot the graphs for the relationships between *L_Aeq* and Z^∞ for tarmac and dirt roads. The linear regression graphs between *L_Aeq(T)* and Z^∞ had *R²* of 83.6 and 97.0% for the tarmac (Figure 3a)

and dirt roads (Figure 3b) respectively [13]. *R²* value of 100 % is considered to be the best fit, while any value above 70 % is considered to be a good correlation between the variables [16]. For WBV, the curve fit method with quadratic polynomial regression was used to plot the graphs for the relationships between *VDV(8)* and Z^∞_{3D} for the tarmac and dirt roads. The quadratic-linear regression graphs between *VDV(8)* and Z^∞_{3D} had *R²* of 83.6 and 89.7% for the tarmac (Figure 4a) and dirt roads (Figure 4b) respectively [16]. For HAV, the curve fit method with quadratic polynomial regression was also used to plot the graphs for the relationships between *A(8)* and Z_v^∞ for the both tarmac and dirt roads. A quadratic linear regression graph between *A(8)* and Z_v^∞ had *R²* of 84% for the tarmac and dirt roads (Figure 5) [17]. This shows that the percentage of the *R²* values of each parameter have changed due to change in the value Z^∞ at different vehicle speeds. It also shows the percentage of data that represents the whole plot data on a graph between each parameter with Z^∞. The rest are from other factors that cannot be predicted due to factors that were not examined in this study. The *R²* value can be improved by eliminating the extreme-value data remotely or outliers, and then recalculating *R²*. However, in this study, all the data points are proper and valid. Therefore, they should not be removed from the original calculation.

The average relative errors for the noise exposure model were 1.35 and 1.45% for the tarmac and dirt roads respectively, which are considered within the practically acceptable relative error limits of 10% [13]. In addition, the *R²* values for noise, WBV and HAV exposure models were above 80% for comparison between measured and predicted values (Figure 6, 7, 8). Table 1 shows the noise, WBV and HAV exposure models for the tarmac and dirt roads. In this table, noise and WBV have different models for tarmac and dirt roads. On the other hand, the HAV model has only one model, which combines both types of roads. This is as low *R²* values were obtained for separate HAV exposure models for the two road types graphs, while combining the model combining HAV for the two road types provides high *R²*.
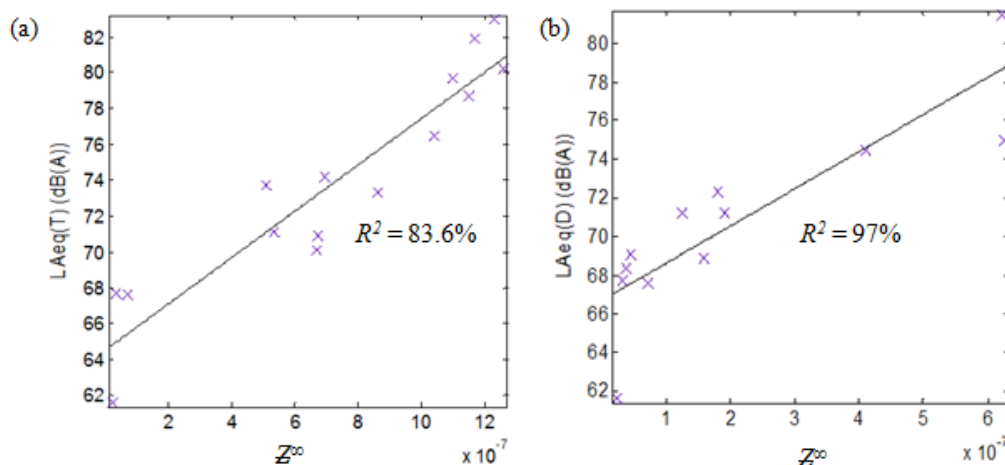

Figure 3 Linear regression graph between sound pressure level and Z^∞ for driving on the (a) tarmac road and (b) dirt roads
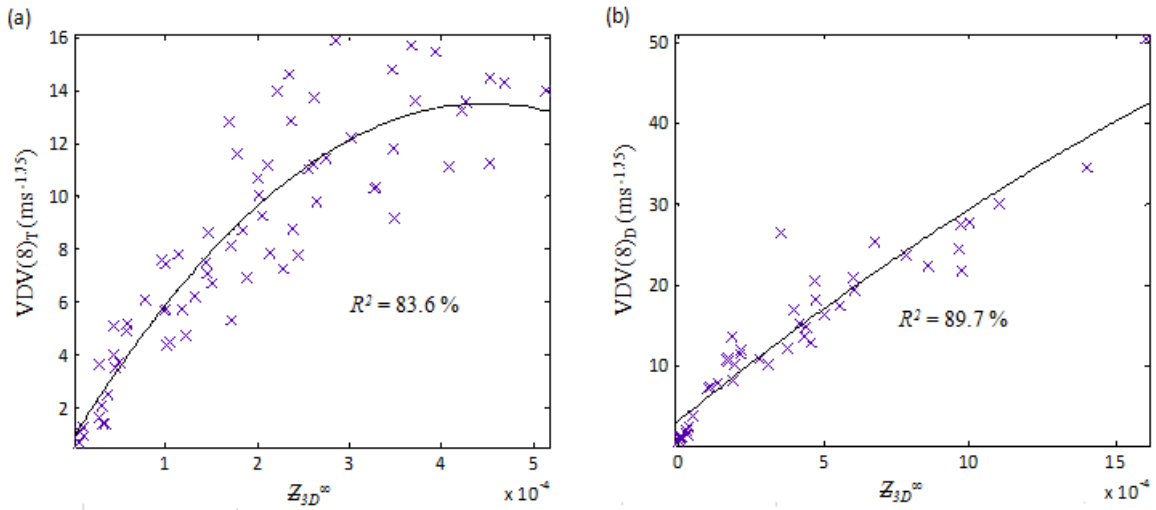
Figure 4 The quadratic polynomial regression graph between *VDV(8)* and $\not Z_{3D}^{\infty}$ for driving on the (a) tarmac and (b) dirt roads.
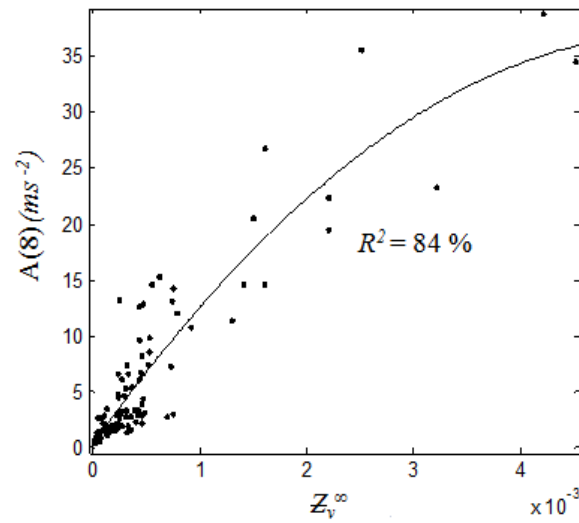

Figure 5 The quadratic polynomial regression graph between A(8) and $\not Z_{v}^{\infty}$ for driving on the tarmac and dirt roads.
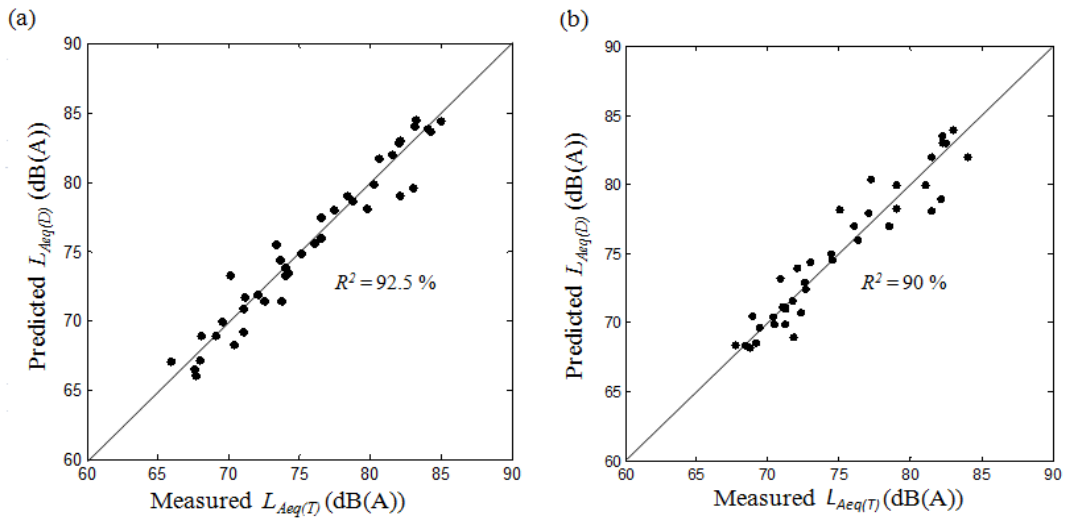

Figure 6 Comparison between predicted and measured noise exposures for the (a) tarmac and (b) dirt roads.
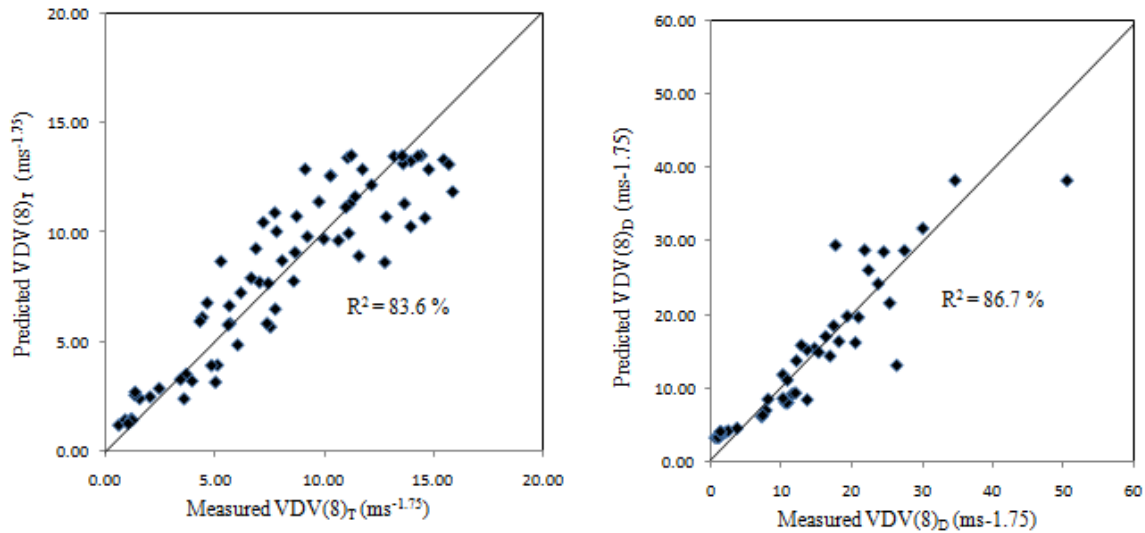
Figure 7 Comparison between predicted and measured WBV exposures from driver's seat for the (a) tarmac and (b) dirt roads
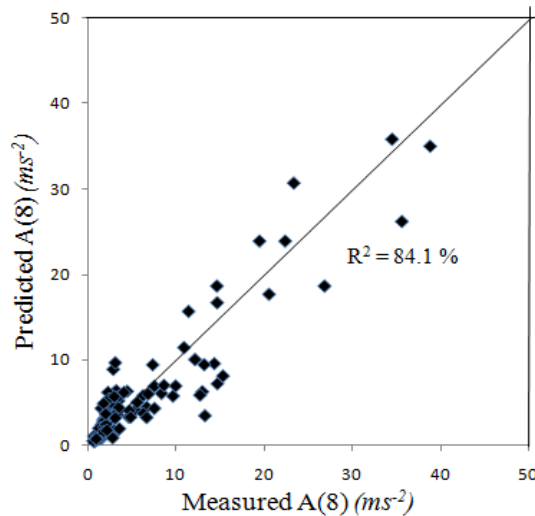

Figure 8 Comparison of predicted and measured HAV exposures from the steering wheel.

With reference to the action level of noise from OSHA (85 dB(A)), and exposure action value (EAV) for WBV and HAV from Directive 2002/44/EC (9.1 ms$^{-1.75}$ and 2.5 ms^{-2} respectively), the allowed I-kaz coefficient (Z^∞), I-kaz 3D coefficient (Z^∞_{3D}) and I-kaz Vibro coefficient (Z^∞_v) values for each models can be determined, as shown in Table 1. By using MATLAB, a graphical user interface (GUI) noise and vibration exposure monitoring system can be developed to monitor exposure to MA drivers. The truck driver will be given a warning such as buzzer sounds or on-screen warning displays if the noise, WBV and HAV recorded reach the EAV indicated in Table 1. Drivers are advised to take a break from continuous driving or reduce the speed of the vehicle if the system gives a warning alert.

Table 1 Noise, WBV and HAV exposure models for tarmac and dirt roads.

	Tarmac roads	Dirt roads
Noise	$L_{Aeq(T)} = 1.135 \times 10^7(Z^\infty) + 65.67$	$L_{Aeq(D)} = 1.663 \times 10^7(Z^\infty) + 67.79$
	Allowed Z^∞ action value = 1.703× 10^{-6}	Allowed Z^∞ action value = 1.035× 10^{-6}
WBV	$VDV(8)_T = -6.319 \times 10^7(Z^\infty_{3D})^2 + 5.663 \times 10^4\left(Z^\infty_{3D}\right) + 0.8192$	$VDV(8)_D = -3.084 \times 10^6(Z^\infty_{3D})^2 + 2.941 \times 10^4(Z^\infty_{3D}) + 3.092$
	EAV; $Z^\infty_{3D} = 1.84 \times 10^{-4}$	EAV; $Z^\infty_{3D} = 2.089 \times 10^{-4}$
HAV	$A(8) = -1.234 \times 10^6(Z^\infty_v)^2 + 1.344 \times 10^4(Z^\infty_v) + 0.333$	
	EAV; $Z^\infty_v = 1.637 \times 10^{-4}$	

5.0 CONCLUSION

This paper discussed on the development of a noise and vibration exposure monitoring system for MA drivers while driving three-tonne trucks. This system is a combination of three models, namely noise, WBV and HAV, which are the NHV parameters that are closest to the driver while driving the vehicle. The noise exposure model was developed using a regression model based on I-kaz™ between the noise exposure and Z^∞. The noise, WBV and HAV models were developed using I-kaz™, I-kaz 3D and I-kaz Vibro respectively. The performance of the predictions using the developed models had high R^2 values and low average relative errors, indicating that the estimated results are accurate and encouraging to be applied in a noise and vibration exposure monitoring system inside the driver's cabin of MA three-tonne trucks.

In the recent 10th Malaysian Pelan (RMK10), the Malaysian government procured a few types of tracked vehicles, including the Pendekar PT-91M main battle tank. These vehicles are frequently used, and, similar to wheeled vehicles, expose the drivers to noise and vibration. Therefore, the study on noise and vibration that has been conducted for wheeled vehicles should be extended to tracked vehicles. This will be followed by the recommendation of an appropriate a system for monitoring noise and vibration in tracked vehicles.

Acknowledgement

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