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Empirical Model of Ground-Borne Vibration Induced by Commuter Railway Traffic

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ABSTRACT

Train-induced ground-borne vibration has a negative effect on residential areas near railway tracks. Residents who are regularly exposed to ground-borne vibration can experience sleep disturbances and more serious health problems in the long run. In addition, it concerns the mental health of those who live nearby. Residents' productivity and quality of life can be harmed as a result of direct exposure to train-induced ground-borne vibration. The relevant authorities must record a few precise measurements using technically sophisticated instruments and equipment to research further the impact of ground-borne vibrations induced by train traffic. However, the equipment is usually costly, and it has become one of the main stumbling blocks to achieving the desired results. This paper aimed to propose an alternative to the authority's current guidelines and standards for vibration limits and environmental control. This research established a regression prediction model to forecast the peak particle velocity of commuter train ground-borne vibration. The established model considered a few parameters obtained from site surveys with limited or no tools at all. The data collected was measured along the ground rail tracks involving human-operated trains. Residents living in landed residential areas near railway tracks were selected as the recipients. Finally, the peak particle velocity models were established, validated, and a sensitivity analysis was carried out.

Keywords: Commuter train, empirical model, ground-borne vibration, peak particle velocity

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INTRODUCTION

It is important for businesses or companies involved in constructing of a new railway system to develop a predictive method that allows for the prediction of vibration levels in the early planning stages of new railways, which may be in the form of cost-effective vibration countermeasures. However, while designing a new railway line or increasing the capacity of an existing one, the designers are constantly concerned about how far from the railway would be disturbed beyond regulation, resulting in how many residences would have to be relocated. Many prediction models, such as the analytical, numerical, and scope models, have been established in recent years. Despite the widespread use of numerical methods in recent studies, field test analysis is still essential to give direct evidence to validate various prediction models. Meanwhile, research is being carried out to reduce vibration caused by railways (Hu et al., 2018).

Because of its potential consequences on the comfort of local citizens, the long-term preservation of historic buildings, and the operation of precision instruments, the problem of train-induced vibrations is receiving more attention (Ma et al., 2020). Furthermore, as residents' living standards rise, the demand for and emphasis on environmental quality is becoming more important. Vibration pollution refers to ground vibrations caused by railway and other traffic vehicles, and human activities that have a negative impact on human comfort and the psychological health of those living near the source of the vibration. The ground-borne vibrations will also impact the protection of buildings, the functioning of sensitive machinery and instruments, and the working conditions in the affected areas.

This research sought an alternative to the local authority guidelines on vibration limits and control based on the local environment and conditions. This study combined Malaysian railway traffic, environment, and geological conditions to establish an empirical model for ground-borne vibration prediction. The developed empirical model should to predict the ground-borne vibration induced by railway traffic operating on a railway system, particularly during the planning phase of projects and mitigation measures. This research is fundamental in constructing high-speed railway systems since high-speed train service is expected to cause greater ground vibrations. The operation of a high-speed railway system in Malaysia is currently in the planning stages. The established model is expected to aid the authority in addressing ground-borne vibrations if the railway system is built.

This research project is intended to fill a knowledge gap in the fundamental understanding of ground-borne vibration, which comprises many branches of knowledge about local rail traffic conditions. The study was motivated by limited findings regarding the degree of perceived irritability and annoyance experienced by affected people living near the source of the vibrations, especially in Malaysia. Therefore, this thesis attempted to collect empirical data by installing a few basic instruments at the study site to test the vibrations caused by railway traffic.

LITERATURE REVIEW

Propagation

After ground-borne vibrations are produced in the railway, vibrations typically spread to the surrounding area through the soil media. Propagation characteristics are influenced by soil properties, parameters, and distance from the source. The type of soil has a significant impact on ground vibration; the stiffer the soil, the lower the ground vibration attenuation effect (Kuo et al., 2017). Ground vibration will be quickly attenuated as the distance along with the ground transmission path increases. Ground vibration in stiff or hard soil could be attenuated and absorbed considerably faster over time than in soft soil. The frequency of soft ground is lower than that of rigid or hard ground. In the soft ground profile zone, the ground vibration frequency ranges from 5 to 10 Hz. Vibrations in the ground at these low frequencies may travel further away from their source. The main factor that affects substantial ground vibration that can cause discomfort to people who live 100 to 200 meters away from the rail tracks is soft soil formation, such as silt or soft clay (Madshus et al., 1996).

The most well-known and widely used vibration measurement is the peak particle velocity (PPV), which measures the rate of vibration. The majority of guidelines and regulations use PPV to determine vibration thresholds. The peak particle velocity for each observed waveform is defined as the maximum particle velocity over the total recorded time. Thus, the PPV is the maximum instantaneous velocity at a point in a given time interval. As a disturbance from a source of waves propagates outward from the source with a certain amount of wave velocity, ground particles vibrate with varying particle velocity. The motion is represented in three perpendicular components (usually transverse, vertical, and radial or longitudinal). All three components must be calibrated at the same time to ensure that the PPV is determined correctly (Avellan et al., 2017).

The Impact of Speed on Ground Borne Vibrations

One of the variables that influence the level of the ground-borne is train speed. As expected, increasing train speeds will result in higher ground-borne vibrations (Shih et al., 2018). The vibration frequency normally increases by 4 to 6 dB as the train's speed is raised. Fesharaki and Hamedi (2016) have demonstrated that the vibration level rises as the speed rises. They also demonstrated that when train speeds reach 200 km/h, vibrations increase dramatically. The relationship between train speed and ground-borne vibrations was also discovered by Connolly et al. (2014). The study was able to show that, despite the fact that the vibration receivers are located at different locations, the relationship between train speed and vibration levels is the same, with vibration levels predicted to rise as train speed increases.

The Impact of Distance on Ground Borne Vibrations

The distance between the receivers and the source of vibrations significantly impacts the level of ground-borne vibrations (Ibrahim et al., 2018). Theoretically, as the distance between the vibration sources and the receiver decreases, the ground vibration will increase. Regardless of the form of soil, Fesharaki and Hamedi (2016) demonstrated that the longer the distance between sources and receiver, the lower the vibrations. Based on field analysis, Connolly et al. (2014) found that vibration detected near the rail track was higher than vibration detected further away from the rail track.

Established Standard and Guidelines on Human Annoyance

The magnitude of a vibration can be determined in several ways. Velocity (mm/s), displacement (mm), and acceleration (mm/s^2) are the three most used methods for determining vibrations (Eitzenberger, 2008). The velocity (mm/s) was employed in this investigation since the data were compared to the values recommended by the standard Malaysian guidelines. The magnitude of vibrations is measured using velocity in the standard guidelines. The International Standards Organization (ISO) published the *Guide to the Evaluation of Human Exposure to Vibration and Shock in Buildings (1 Hz to 80 Hz)* (ISO, 1997). The ISO stated that 0.2032 mm/s is the allowable response of a human to continuous vibration from traffic for the residence area. Most countries throughout the world utilise this ISO standard as a reference for developing their standards. Therefore, vibrations have varying limits in different countries based on local conditions. Table 1 summarises the different limits of vibrations for residential among the countries.

Table 1
Different limits of vibrations for residential among the countries

Country/Standard	**Vibration limits (mm/s)**
United State (Bahrekazemi, 2004)	0.2540
Norway (David et al, 2015)	0.6000
Sweden (David et al, 2015)	0.4000
California (California Department of Transportation, 2013)	0.3048
The Netherlands (Patrick & Michel, 2012)	0.8000
Malaysia (Department of Environment Malaysia, 2007)	0.5670

According to most countries' guidelines, the highest vibrations limit for human response and annoyance is valued below 0.8 mm/s. However, in Malaysia, the suggested limits for human response and annoyance in commercial areas are 1.176 mm/s, greater than the 0.567 mm/s in residential zones.

Review of Prediction Model from Railway Traffic

Model development aims to either describe or estimate and forecast the ground vibration phenomenon. If the established models can solve problems and make accurate predictions of ground-borne vibration in real-world conditions, they are important and useful. Ground-borne vibration prediction models are expected to include at least three basic elements: the receiver, the source, and the propagation direction.

Despite the fact that there are numerous ground vibration prediction models available, unique models for predicting ground vibrations in Malaysia have yet to be created. Therefore, many other researchers have used Madshus et al. (1996) model as a primary reference when developing new vibration prediction models.

$$V = F_V F_R F_B = [V_T F_S F_D]\, F_R F_B \qquad [1]$$

Equation 1 shows the formula for the created by, where F_v is the basic vibration function, F_R is the track quality factor, and F_B is the building amplification factor. The basic vibration feature comprises three-element: the specific type of train vibration level, V_T, the reference distance D_O of 15 m, and the reference speed, S_O is 70 km/h on a standard track and embankment. A reference distance of 15 m was determined to prevent the influence of nearby field waves. F_S is a speed factor that considers the impact of the train's speed, S. $F_S = \left(\frac{S}{S_0}\right)^A$ is how the F_S is represented. A, where A denotes the train's speed exponent. F_D is a distance factor, with the expression of $F_D = \left(\frac{D}{D_0}\right)$. D is the distance of the embankment or track's core to the recipient, and B is the distance exponential value. Based on vibration measurements, it has been determined that ground conditions, train type, line quality and embankment design, train speed, distance from track to building, and building condition are the most important factors for low-frequency railway induced vibration on soft ground and its effect on neighbouring houses. The model assumes that the impacts of components of train type, line quality and embankment design, train speed, distance from track to building, and building condition are separable and that the factors, in principle, fluctuate with the ground conditions. Ground conditions, type of train, line quality, and type of buildings have been divided into small groups to make the model a convenient planning tool. Suhairy (2000) also developed a prediction model based on Madshus et al. (1996) model. Equation 2 shows the formula established by Suhairy (2000).

$$V = V_T * \left(\frac{D}{D_0}\right)^B * \left(\frac{S}{S_0}\right)^A * F_R * F_B \qquad [2]$$

This formula can calculate vibration velocities for various train types and distances between the source and receiver. V_T represents the vibration levels caused by trains at 20m and 70 km/h, D represents the distance from the track's middle, and D_O is set to 20m to avoid the effects of nearby field waves. B is distance-based, with different values depending on the train type. S stands for train speed, and S_O is set to 70 km/h for all types of trains. Madshus et al. (1996) assume that A is the speed-dependent exponential and that it is 0.9. The efficiency factor, F_R, is believed to be 0.8, and the building amplification factor, F_B, is set to 2. The essential parameter has been identified using Madshus et al. (1996) formula, and the information that has been measured can be expressed in a generic form using Suhairy (2000) equation for the acquired results for F_R, F_B, F_D and F_S. This equation can be used to calculate the vibration velocities for a variety of train types and distances.

Rossi (2003) developed a simple model to predict the vibrations caused by trains as part of his research. The absolute value of the particle vibration velocity, U, can be calculated using longitudinal and transversal velocities, as shown in Equation 3.

$$U = \sqrt{u_T^2 + u_L^2} \quad (3)$$

where u_T is the particle's root mean square ,r.m.s of the transversal velocity, while u_L is the r.m.s for the longitudinal velocity. Equations 4, 5, and 6 give the formulas for obtaining u_T and u_{TL}.

$$u_T = \sqrt{\frac{J_T}{z_T}} \quad (4)$$

and

$$u_L = \sqrt{\frac{J_L}{z_L}} \quad (5)$$

where:

$$z_T = \sqrt{\rho . G} \quad \text{where } G = \frac{E}{2(1+\upsilon)}$$

$$z_L = \sqrt{\rho . D} \quad \text{where } D = \frac{E(1-\upsilon}{(1+\upsilon)(1-2\upsilon)} \quad (6)$$

Rossi's prediction formula takes into account z_T and z_L mechanical impedances, the soil Poisson's ratio, υ, soil density, ρ, soil torsional elasticity module, G, and soil longitudinal rigidity, D. Rossi (2003) proposed the model for train-induced soil vibration prediction furnishes velocities (longitudinal and transversal) and global vibration level. A measuring campaign along an Italian high-speed train was used to calibrate the model. Paneiro et al. (2015) also predicted the amplitudes of ground vibrations generated by rail traffic. Equation 7 defines the peak vector sum (PVS) in mm/s, calculated using mathematical relationships between the dependent variable and the predictors.

$$PVS = f(D,V,T,B,G) \quad (7)$$

The distance between the source and the receiver is denoted by D, the train speed in kilometres per hour is denoted by V, T predictors for track type, B predictors for building type, and G qualitative predictors for the dominant geology are denoted by G. If energy is taken into account, the train speed from Equation 7 is replaced with W, the kinetic energy. According to the suggested regression model by Rossi (2003), for the investigation of qualitative predictors, all building types evaluated have varied responses to railway traffic vibrations. From another researcher, as shown in Equation 8, Bahrekazemi (2004) summarised a semi-empirical model to predict particle velocity, V.

$$V = (a.speed + b)\left[\frac{r}{r_0}\right]^{-n} \quad (8)$$

r is the source-to-receiver distance, while r_0 is the reference distance, according to this model. Fitting the calculated data with the equation in at least a square sense is needed to determine the distribution of attenuation, *n*. The two parameters known as functions of a wheel force are *a* and *b*, while *speed* is the train speed in kilometres per hour. This prediction unit is measured in millimetres per second. The majority of the train vibration prediction models in this literature have taken into account different factors such as track efficiency, sleeper vibration, building amplification factor, and wheel power. Analysing these factors often necessitates permission from the appropriate authority, which can be viewed as a research gap. By introducing a simplified method of in-situ data collection, this study aimed to bridge the research gap. This study suggested using basic and minimal measurement instruments, or even without specialised equipment, to predict the vibrations caused by railways. The distance between the source and the receiver can be determined with a meter tape or a manual step count, and train speed can be estimated by dividing the distance travelled by trains by the time it takes to run. A standard stopwatch may be used to monitor the time. The values of these parameters can then be used in the models that have been developed. Previous researchers' prediction models differed depending on the geological and environmental conditions of the countries. This study also looked at the geological factors and conditions in the region. The factors or elements that had previously been used in other researchers' developed models were simplified in this study to reduce the reliance on advanced equipment when collecting data to predict ground-borne vibrations using the developed models.

MATERIALS AND METHODS

Case Study

This study was carried out along the Kereta Api Tanah Melayu Berhad (KTMB) railway route, which runs from Padang Jawa in Shah Alam to Klang in Selangor. The railway is a two-way track with two train routes: Kuala Lumpur and Pelabuhan Klang, Selangor. These sites were chosen to distinguish the various vibration magnitudes caused by trains on the railway track. In addition, the locations were chosen because of their strategic locations, as many residential areas along the track were endangered by ground-borne vibration caused by trains. This study also concentrated on areas with landed type residential buildings.

Because of landed residential buildings in the areas adjacent to the railway track, the route was chosen. There are no vibration barriers in the vicinity of the case study sites. For this analysis, the distance between the residential area and the rail track is less than 30 meters. Train parameters, such as train speed, were collected in the field during the

Figure 1. Aerial view of site location for the lane of Padang Jawa Station to Bukit Badak Station consists of site 1, site 2 and site 3

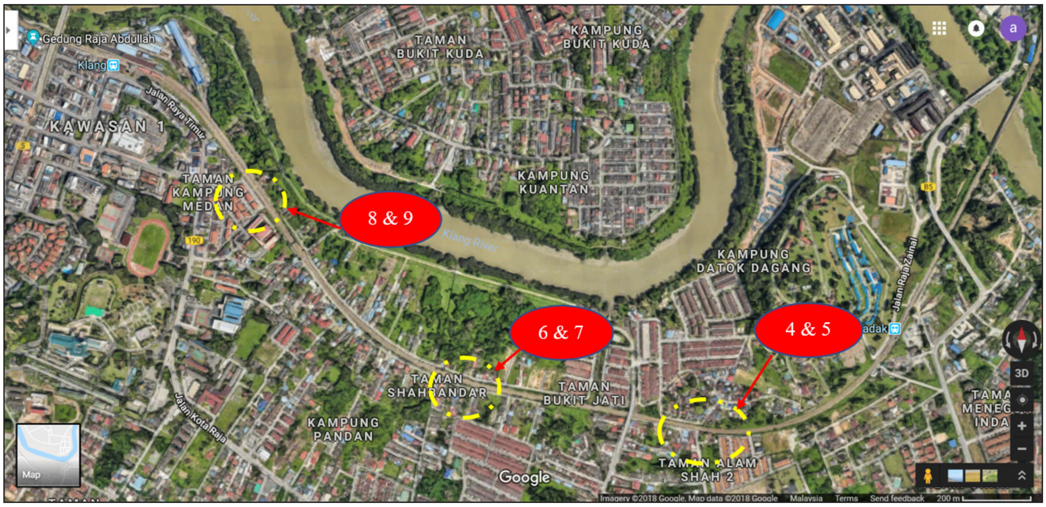

Figure 2. Aerial view for site 4 until site 9 located along the lane of Bukit Badak Station to Klang Station

site survey. Radial vertical and horizontal wave vibrations make up the ground-borne vibration velocity measurements. The data was collected using a seismograph mounted at the locations. Three sites were selected, ranging from Padang Jawa station to Bukit Badak station. The remaining six sites are in the vicinity of Bukit Badak Station and Klang Station. As a result, a total of nine (9) stations were selected. The locations were selected to be as close between the track to the landed residential areas as possible. Different sites were chosen to achieve different train speeds and distances from the residential areas to the sources. Part of the most populated areas in Malaysia is Shah Alam and Klang, which have one of the highest populations. Figures 1 and 2 depict aerial views of the site positions between Padang Jawa Station in Shah Alam and Klang Station in Klang, from Site 1 to Site 9.

Instrumentation and Equipment Strategy Setting Up

The measurement equipment consists of the following parts to collect valuable data to study the ground vibrations: a pick-up sensor or transducer, an amplifier, a level indicator or amplitude or a recorder with a signal analyser. Filters (low pass, high pass) should be used to restrict the equipment's frequency spectrum and add the necessary filters to the input signal, where applicable. The vibration transducer, the auxiliary equipment, including amplifiers, variable frequency equipment and carrier systems, must comply with the standards (Department of Environment Malaysia, 2007). Figure 3 shows an example of the vibration measurement system. The transducer is used to measure vibration by translating one form of energy to another. The magnitude of the ground-borne vibration can be measured in velocity, displacement and acceleration at the site.

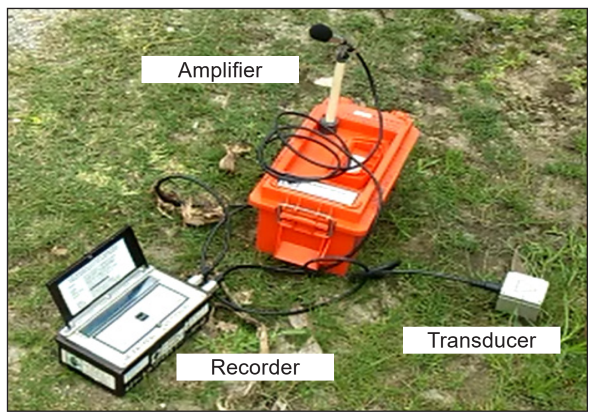

Figure 3. Components of vibration measurement

The relationship between the parameters for the ground vibration's magnitude is shown in Equations 9 and 10 (California Department of Transportation, 2019).

$$D = V/ 2\pi f \quad [9]$$

and

$$a = 2\pi fV \quad [10]$$

where:

D = displacement (amplitude) (mm)
V = particle velocity (mm/s)
f = frequency (Hz)
a = acceleration (mm/s²)

Vibration transducers that are normally used comprise the geophone and the accelerometer. The accelerometer normally detects measurement of strong ground motion, and weaker ground motion is normally measured using the geophone. It is due to an accelerometer's larger amplitude detection than a geophone (Hons et al., 2008). Figure 4 shows the geophone installation at a railway track to measure the vibrations induced by trains conducted by Crespo-Chacón et al. (2016). In vibration measurement, a geophone detects three orthogonal axes of vibration, which are in the radial, vertical and transverse direction

The range of measurement using a geophone can start from the value as low as 0.063 mm/s up to 30.5 mm/s (Sulaiman, 2018). Zhang et al. (2016), Adnan et al. (2012) and Bahrekazemi (2004) were among the researchers who measured and recorded the ground vibration using accelerometers. Figure 5 shows an accelerometer installation at the site conducted by Zhang et al. (2016).

For measuring excessive ground-borne vibration from high-speed trains, several types of accelerometers are available. The dynamic limit of measurement by accelerometers for ground-borne vibrations varies from the value of 0.01 mm/s^2 to more than 50 000 m/s^2.

Figure 4. Geophone was installed at the study site by Crespo-Chacón et al. (2016)

Figure 5. Example of accelerometer installation by Zhang et al. (2016) on railway-induced building vibrations experiment

Based on the local guideline by Malaysian authorities, the analysis for vibration frequencies within the range of 1 to 100 Hz should utilise analysers or signal analysers with one-third octave-filter sets or narrowband FFT (fast Fourier transform). These can either be instrumentation hardware or digital signal processor software. This usage of the equipment must be according to the manufacturer's instructions (Department of Environment Malaysia, 2007). The suitability of the measurement equipment, namely the geophone, accelerometer or strain gauge, depending on the vibration amplitude and frequency required in the study. As for this research, due to its accuracy aspect and the availability of the equipment, a seismograph was chosen to calculate the low ground vibration magnitude near the railway tracks.

A seismograph meter, also known as the Mini-SEIS, was used to perform four repetitions of data reading and measurements for each site position for this analysis. A Mini-SEIS is made up of a microphone, a geophone transducer, and a data logger display (White Industrial Seismology Inc., 2009). The data was collected and categorised into two groups: peak and non-peak hours at two different distances at each site location. It was done because it was assumed that the load borne by the trains would vary between peak and non-peak hours. After all, peak hour passenger numbers were projected to be higher. Figures 6 and 7 provide a detailed diagram of where the Mini-SEIS should be mounted. Two data collection sessions were performed in the morning for the experiments, with each session

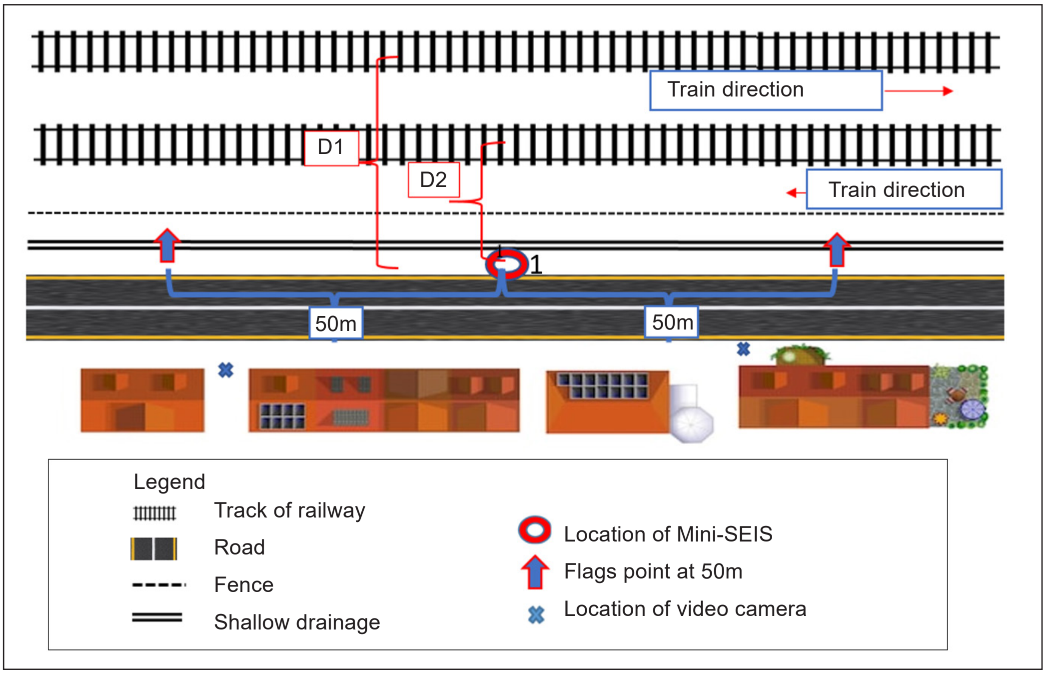

Figure 6. The location of Mini-SEIS at location 1 for morning session and midnight session of each site locations

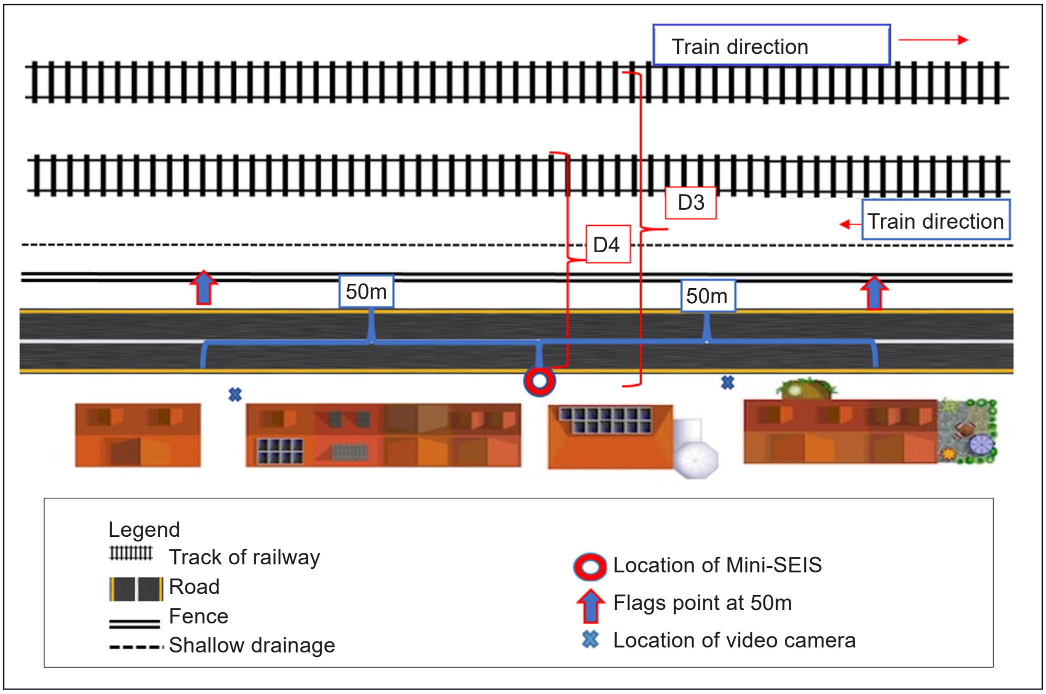

Figure 7. The location of Mini-SEIS at location 2 during the evening session of each site location

consisting of a two-hour experiment. First, it was done to gather data on peak and non-peak hour sessions. Then, two sessions were performed in the evening to collect peak and non-peak hour data from the Mini-SEIS sources at different distances. The data collection timeline is shown in Table 2: Figures 6 and 7 show where the Mini-SEIS is located.

Table 2
*The timeline of data collection is based on the location of Mini-SEI*S

Time		Location of mini-SEIS and distance taken	Type of Train
Peak Hour	**Non-peak Hour**		
6.30am – 8.30am	9.00am – 11.00am	1 = d1 & d2	Commuter
5.30pm – 7.30pm	3.00pm – 5.00pm	2 = d3 & d4	Commuter

Note: Location of mini-SEIS 1 & 2 and distance d1,d2,d3 and d4 refer to Figure 5 and Figure 6

A Mini-SEIS digital seismograph was used to measure ground vibrations in this analysis. As shown in Figure 8, the microphone and geophone transducer were mounted on residential areas and connected to a Mini-SEIS display. A GPS meter was used to calculate the Mini- SEIS's coordinates. The times shown by the Mini-SEIS were recorded to match the actual time of the trains passing by the designated points to denote the data during data processing. The Mini-SEIS was installed outside the KTMB fencing gate on the railway tracks.

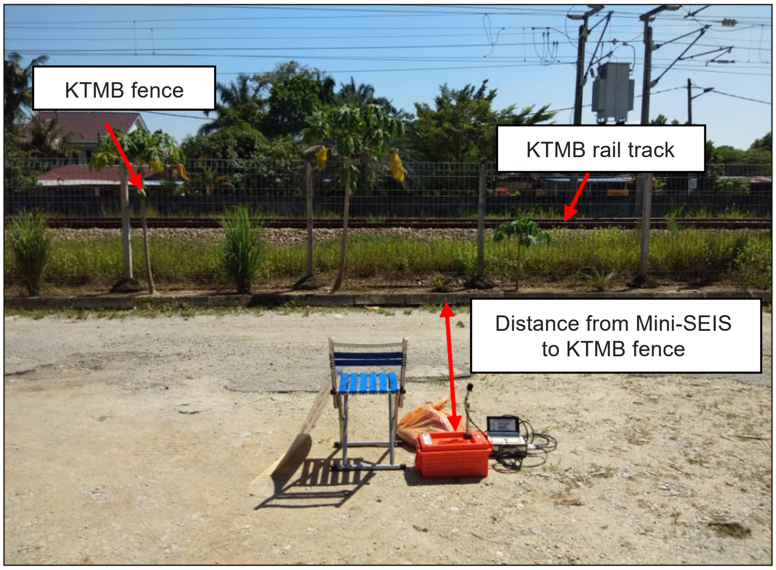

Figure 8. Installation of Mini-SEIS at the study area

The Mini-SEIS was installed within a 25 meters radius of the rail track. This distance was deemed adequate for this analysis because houses within this range allow for assessing human discomfort induced by the vibration.

RESULTS AND DISCUSSION

Threshold Limit for Allowable Limit Based on Malaysian Standard

Figure 9 shows the scatterplot of the peak particle velocity induced by the railway traffic in comparison with the allowable limit of vibration based on the guideline fixed by the Malaysian Department of Environment (DOE).

The recommended limit for human annoyance set by the authority guideline with regard to the steady-state vibrations is 0.567 mm/s for residential areas. The result in Figure 9 shows that most of the vibration induced by the train travelling along with the sites under study were more than the allowable vibration limit stated in the guideline for human annoyance. The vibration values obtained were even higher than the recommended vibration limit for commercial areas taken from the similar guideline, 1.176 mm/s. All other international standards state that the allowable vibrations limit with regard to human annoyance is not more than 0.8 mm/s. The results from this study revealed that the vibration values induced by the trains were way above the allowable limits.

Moreover, the results also showed that the vibrations induced along the study sites exceeded the recommended limit for commercial areas despite being residential. Therefore, it contributed to a higher perception of annoyance among the residents of the affected areas. A similar trend of results was also obtained by most of the researchers such as Zapfe et

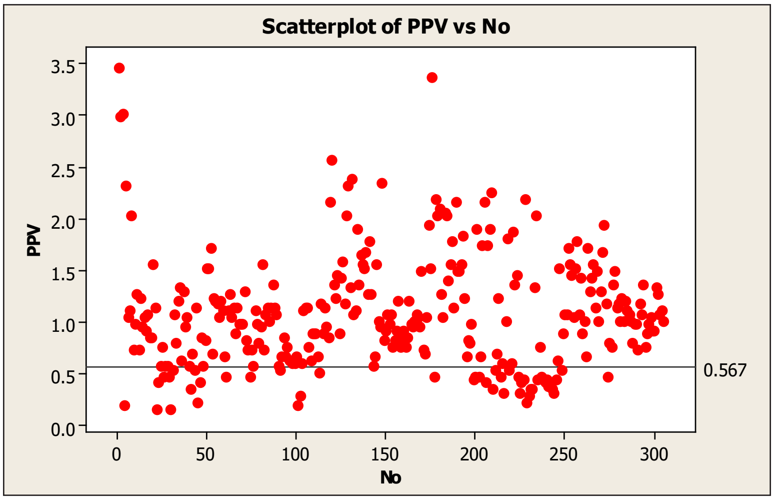

Figure 9. Scatterplot of PPV comparison with the allowable limit set by the authority guideline
Note. The red line (0.567 mm/s) is the allowable vibration limit with regard to the human annoyance level set by the Malaysian authority in residential areas. The green line (0.8 mm/s) is the average allowable vibration limit of human annoyance in other countries. The black line (1.176 mm/s) is the allowable vibration limit of the human annoyance level set by Malaysian authorities in commercial areas.

al. (2012) from the United States and Maclachlan et al. (2018) from Sweden, whereby in their research, vibrations induced by trains had exceeded the allowable limit of perceived annoyance by humans when they comparisons were made against their countries' guideline set by the local authorities. Therefore, the finding of the results that shows on the human annoyance towards ground-borne vibration induced by train is exceeding allowable limit from the standards and give motivation to this paper produce a model to predict the vibration value from the trains.

Descriptive Statistic of the Empirical Peak Particle Velocity Data

The descriptive statistics encapsulated the empirical peak particle velocity data analysis, which included all variables such as mean, maximum, minimum, median, skewness, kurtosis value, and standard deviation. Therefore, extreme values may be identified throughout the screening phase using the descriptive statistic's performance. Table 3 shows the empirical peak particle velocity data after the screening, in which the extreme values

Table *3*
Descriptive statistic for the commuter PPV

Variable	Mean	StDev	Minimum	Median	Maximum	Skewness	Kurtosis
PPV	1.0405	0.4762	0.1588	1.0160	2.3813	0.59	0.04
s	41.67	17.05	16.00	`40.00	83.00	0.33	-1.12
d	12.10	5.16	4.23	11.71	25.70	0.85	0.55

PPV = peak particle velocity (mm/s); s = speed (km/h); d = distance (m) for commuter train engineering parameters were identified. The extreme values were identified as errors during the peak particle velocity data inspection during the data input phase. An error should be eliminated to prevent more comprehensive mistakes during the model development process.

Correlation Analysis for the Commuter Peak Particle Velocity Parameters

The method of diagnosing the possible relationship between the dependent and independent variables used in developing regression models is correlation analysis. The following is the correlation research hypothesis:

H_0 = There is no correlation between two variables

H_1 = There is a correlation between two variables

Correlation analysis was used to test all possible variable combinations, and the results for the overall variables are shown in the Table 4 correlation matrix. The r-value and p-value are in each column. Thus, the r-values are at the top of each row, and the p-values are at the bottom of each row.

Table 4
The correlation matrix among variables

	Peak Particle Velocity (mm/s)	***s***
Speed of train (km/h)	0.502	-
	0.000	-
Distance (m)	-0.626	-0.239
	0.000	0.000

For the empirical data obtained from the site, Table 4 shows the correlation values between the variables PPV, *s*, and *d*. *d* was found to have a stronger relationship with PPV (r-value > 0.5). However, since the p-values were less than 0.05, both variables were assumed to impact the PPV significantly.

Multiple Linear Regressions

The commuter peak particle velocity (PPV) was used as the response in the multiple linear regressions, while the train speed (*s*) and distance (*d*) were used as predictors. The constant values and predictors are shown in Table 5.

Table *5*
*Multi linear regression model for commuter P*PV

Predictor	**Coef**	**SE Coef**	**T**	**P**	**S**	**R-Sq**
Constant	1.20601	0.0807538	14.9344	0.000		
Speed	0.01043	0.0012165	8.5755	0.000	0.329780	52.4%
Distance	-0.04960	-0.040217	-12.3319	0.000		

The hypothesis for the final estimating mode is declared as follows:

H_0 = The predictor cannot be used for estimation in the PPV model

H_1 = The predictor can be used for estimating in the PPV model

Table 5 lists the variables for the commuter train model that were significant with the independent variables for estimating the PPV and had p-values of less than 0.05 in the multiple linear regression. The null hypothesis (H0) was rejected, while the alternative hypothesis (H1) was accepted. As a result, these predictors may be used in the model to estimate commuter PPV. The constant value's standard error coefficient was 1.20601. In the meantime, the speed was 0.01043, and the distance was -0.04960. As a result, each variable's standard error was small values, meaning that it was dependable in predicting the population parameter. The R-squared (R^2) value indicates how well the model fits the results (Minitab, 2010). In the linear relationship between the predictor and the response, the S value was 0.329780, which reflected the prediction of the variance of the results. Thus, the linear relationship between the predictor and the response is regulated by R^2. The R^2 value used in the model's development was 52.4 per cent of the variances.

The analysis of variance (ANOVA) allocation of the output is shown in Table 6. Therefore, this test's hypothesis can be determined as follows:

H_0 = The PPV model cannot be used for estimation

H_1 = The PPV model can be used for estimation

Table *6*

*Analysis of variance for Commuter mod*el

Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	2	31.850	15.925	146.43	0.000
Residual Error	266	28.929	0.109	-	-
Total	268	60.779	-	-	-

Table 6 shows that the p-value was less than the 0.05 α-level, indicating that H_1 was accepted and H_0 was refused. As a result, if empirical speed and distance data were used, the regression model was significant and could elaborate or forecast commuter PPV. Finally, the model for estimation was developed as shown in Equation 11 as the commuter PPV regression equation.

$$PPV_{Commuter} = 1.21 + 0.0104s - 0.0496d \quad [11]$$

Where:

$PPV_{Commuter}$ = Peak Particle Velocity (mm/s) for commuter train

s = Speed of train (km/h)

d = distance (m) from receiver to sources

The coefficients for the essential variables in this model are shown in the equation. The positive sign of speed indicates that increasing speed will increase the PPV while decreasing the distance between the source and the receiver will increase the PPV. The model's parameter considerations were similar to those found in a study by Paneiro et al. (2015), who discovered that only speed and distance significantly impact the magnitude of ground-borne vibrations.

Justification of the Regression Model Assumptions

The following process in the analysis was to check the residual plots to see if the model was acceptable and if the regression forecast had been identified. The residual plots show the characteristics of the fitted and observed response values. For example, the residuals versus suits value plot for commuter PPV is shown in Figure 10. The residual plots are dispersed randomly in the diagram, and the plot scattered close to the horizontal line has nearly zero residuals. As a result, there was no proof of missing terms or non-constant variation (Minitab, 2010).

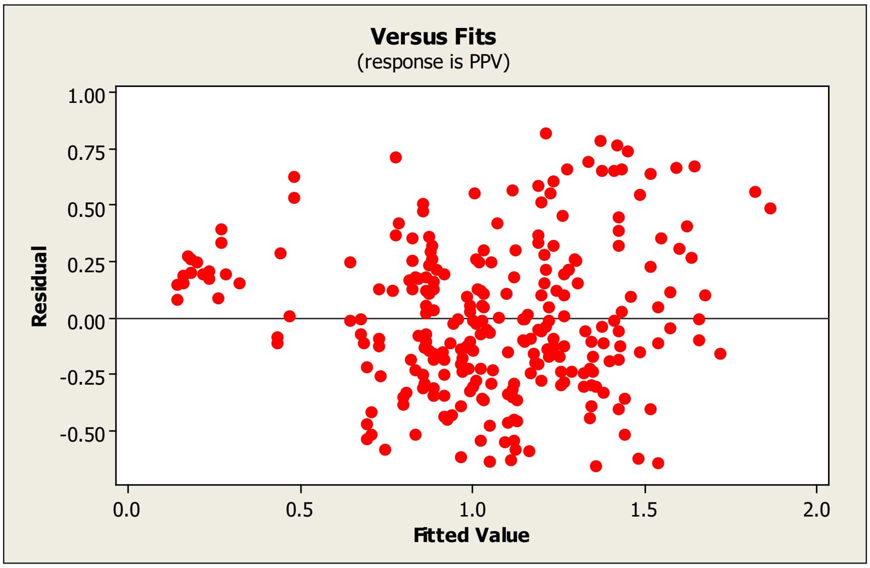

Figure 10. Graph of residuals versus fitted values for commuter PPV prediction model

Normality Test for Residuals of Commuter PPV Prediction Model

The goodness-of-fit test and probability plots such as the Kolmogorov Smirnov and Anderson Darling normality tests are used to decide if the residuals are normally distributed. The points are scattered closely along the straight line in Figures 11 and 12, indicating that the residual was normally distributed.

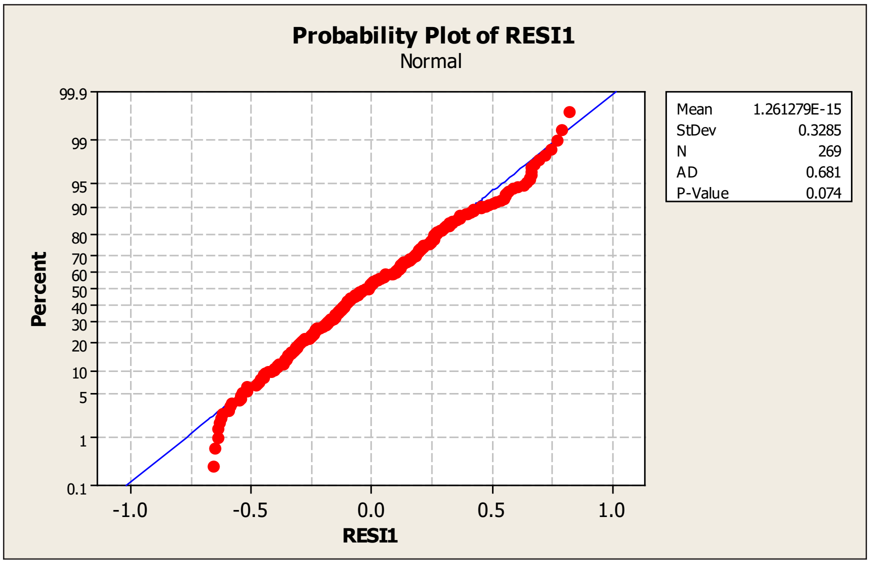

Figure 11. Anderson Darling normality test for commuter PPV prediction model

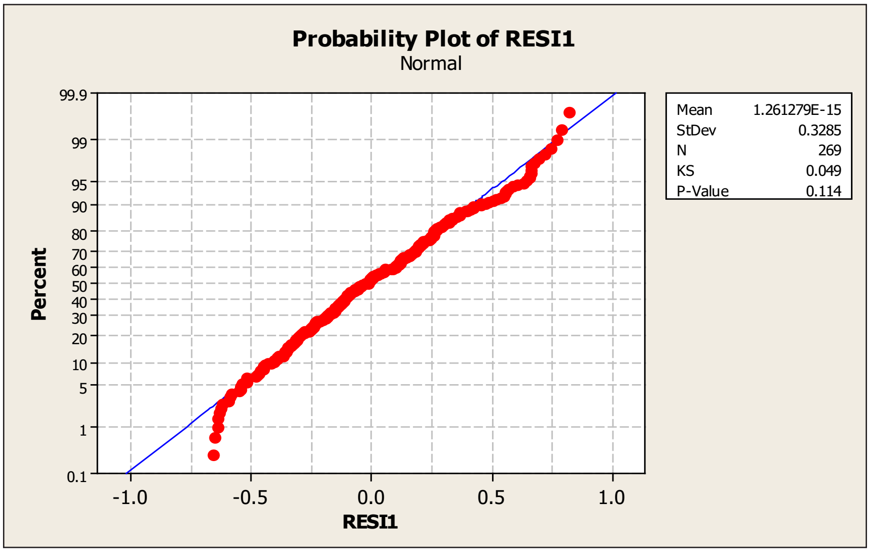

Figure 12. Kolmogorov Smirnov normality test for commuter PPV prediction model

The following are the hypothesis tests for the Kolmogorov Smirnov and Anderson Darling normality tests:

H_0 = The residuals for the predicted model are normal.

H_1 = The residuals for the predicted model are not normal.

The H_0 hypothesis was accepted because the residuals followed a normal distribution curve, and the p-values of the Anderson Darling and Kolmogorov Smirnov normality tests were greater than 0.05.

VALIDATION OF THE COMMUTER MODEL

The developed PPV model for commuter trains must be tested to determine if it can accurately reflect the real-world situation and condition to explain variability in a sample other than the one used to create the model.

Scatterplot of the Commuter Model

Figure 13 depicts the relationship between the empirical PPV and the predicted PPV established in this study for commuter trains.

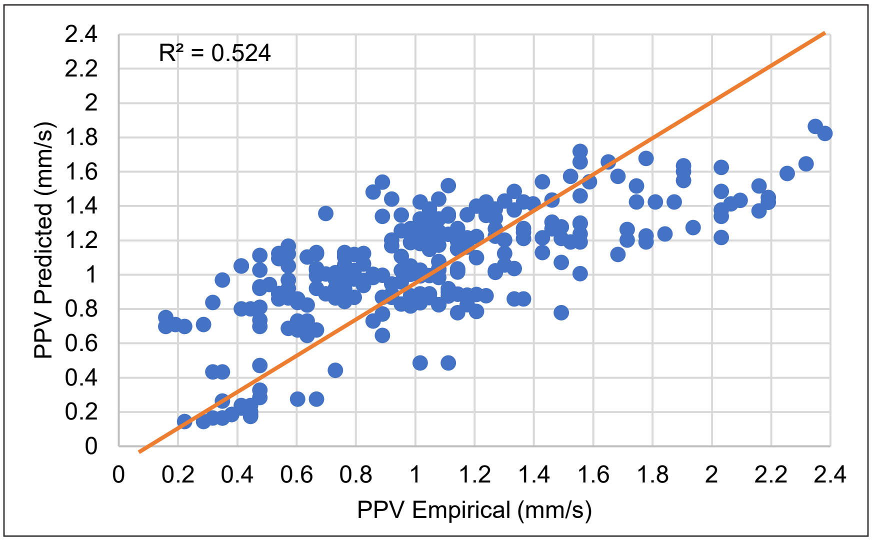

Figure 13. Predicted PPV versus empirical PPV [PPV empirical is denoted as PPV empirical (mm/s) and PPV predicted using Equation 11 is denoted as PPV predicted (mm/s)]

RMSE, MAE and MAPE of PPV Model

The RMSE, MAE, and MAPE of the PPV for the predicted commuter train model are compared in Table 7.

Table 7
RMSE, MAE and MAPE for PPV commuter

MODEL	RMSE (mm/s)	MAE (mm/s)	MAPE (%)
PPV Commuter	0.32795	0.2673	26.8211

The RMSE deviation from the empirical value of PPV was 0.328 mm/s, as shown in Table 6. The PPV's MAE deviation from the empirical value was 0.267 mm/s. The MAPE for PPV calculated from the empirical value was 26.8%. As a result of the small discrepancy values from the RMSE, MAE, and MAPE, the PPV model for commuters can be considered acceptable for predicting the peak particle velocity caused by the commuter train.

Comparing the Mean for PPV Empirical with PPV Predicted using Paired T-test

Mean comparison was made between predicted PPV and PPV from observed data using the validation data set shown in Table 8. The following alternative and null hypotheses were used to form the hypothesis:

H_0 = the difference mean for the model is equal to zero

H_1 = the difference mean for the model does not equal to zero

Table 8 shows that the null hypothesis (H_0) was not dismissed at the 5% significance level since the p-value was 0.897, which was greater than 0.05. Thus, the PPV model expected for commuter trains did not differ much from the empirical PPV values.

Table 8
Validation analysis result for PPV from commuter model

Test	Vab
t-statistic	-0.13
p-value	0.897

CONCLUSION

The peak particle velocity of ground-borne vibrations could be determined using the train speed and the distance from the receiver to the sources, according to the equation models developed in multiple linear regressions. The result from human annoyance towards ground-borne vibrations induced by commuter trains at the case study motivates prediction model development. The data show that the vibration levels from the train exceeded the allowable limit from the Malaysian standard, which is 0.567 mm/s. The prediction formula was developed as $PPV_{Commuter} = 1.21 + 0.0104s – 0.0496d$, whereas PPV is the peak particle velocity of the train, *s* is the train speeds, and *d* is the distance from the track to the residential area. For the commuter type of trains, the peak particle velocity of the ground-borne vibration increased almost linearly as the train speed increased. According to the regression model, the distance between the receivers (residential areas) and the sources (train tracks) had a reverse effect on the peak particle velocity of the ground-borne caused by commuter trains. The peak particle velocity of ground-borne vibration decreases as the distance increases, as shown by the equation model. Residents can feel the ground-borne vibrations more strongly the closer their homes are to the tracks. The formula can be implemented to predict the ground-borne vibrations based on the limitation of local condition since the formula achieve the multiple linear regression analysis.

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