INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING VOL. 14 NO. 1 (2022) 296-312

IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Human Response and Annoyance Towards Ground-Borne Vibration Induced by Railway Traffic

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DOI: https://doi.org/10.30880/ijie.2022.14.01.028
Received 18 February 2021; Accepted 23 October 2021; Available online 07 March 2022

Abstract: Limited findings regarding the level of perceived irritability and annoyance experienced by the affected people living near to the source of the vibrations especially in Malaysia has become the ultimate motivation for this study. This paper attempted to gather the empirical data by setting up a few basic instruments to measure the vibration induced by railway traffic at the site under study. The collected data would determine the vibration level and how it affects human annoyance based on the Malaysian standard guideline. In this paper, identifying the vibration level induced by rail traffic can be used to gauge the level of annoyance and discomfort experienced by the residents living close to the railway tracks. This data can be used to mitigate the problems created by the ground-borne vibration in Malaysia. The vibration data were observed to investigate the level of vibration towards the human response and annoyance by comparing the collected data to the standard guidelines. In this study, the receivers of the vibrations were limited to the residents living nearby the railway track along the designated areas under study. This paper is expected to bridge the gap of knowledge regarding the fundamental understanding of the ground-borne vibration that consists of the combination of several branches of learning on the local rail traffic condition.

Keywords: Human annoyance, ground borne vibration, vibration limit, Malaysian standard guideline, trains

1. Introduction

Railway transportation system in Malaysia is transforming to a greater height as the government decided to invest further in the public infrastructure especially in the railway transportation system. A research by [1] discovered that due to the expansion of coverage for the railway transportation, complaints concerning human discomfort and annoyance caused by the ground-borne vibrations induced by the railway traffic were reported to be increasing. Vibration is generated by the rail traffic over a wide range of amplitude and frequencies. Large vibration amplitudes could cause the destabilization of embankments, settlement of foundations, damage to track components, and damage to nearby structures. The vibration produced by railway traffics can be defined as the wave propagation through ground and the structures. The energy produced is able to cause irritability and discomfort or annoyance towards the people living in the affected areas and could adversely affect sensitive machineries. The vibration caused by the movement of the trains would have measurable impacts on the surrounding areas. The impacts are influenced by the type of trains, type of foundations and the quality of the rail track. These factors determine the level of vibration produced [2].

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2. Literature Review

2.1 Ground-Borne Vibration due to Rail Traffic

The phenomenon of vibration induced by train traffic can be interpreted as wave propagation through structures and through the ground. The energy produced can create discomfort to the people living close to the railway tracks and create interference in sensitive machineries. A certain level of response by the residents would be expected due to the movement of the train on certain locations [2]. When the railway track is in operation, it highly likely that ground vibrations would be induced which could affect the neighboring areas. The levels of vibration in the neighboring structures or buildings are dependent on the forces applied to the rails by the train and the attenuation between the buildings and the rails. This attenuation should be designed to achieve the acceptable limit of vibration for the buildings [3].

In general, excessive ground-borne vibration due to the rail traffic has three correlation elements which are between the source, the propagation and the receiver as shown in Fig. 1. The first element of the correlation is the source where vibrations are created, followed by the transferring of the vibrations through propagation and finally, the receiver which usually is the building. Each element has its own parameters and properties that affect the vibration levels. Even though the links or elements function in sequence, is beneficial to study each of the elements separately when designing the vibration-reduction measures [4].

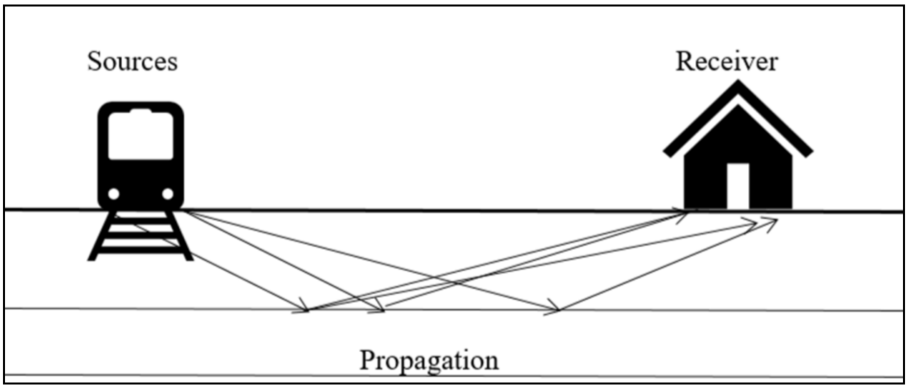


Fig. 1 - The three correlation elements of the ground-borne vibration

2.2 Receiver

The last part of the transmission stage for ground vibrations induced by railway traffic is the receiver. A research by [5] has found that receivers includes the building, the foundation and the surrounding soil. The vibrations propagate from the soil at the foundation and transmitted further onto the building. They may be amplified and cause walls and floors to vibrate. The properties of soil, geometry of the building, type of foundation and the material of the structure are the factors that determine the various effects of vibration in the building structure. In addition, the impact of vibration on a building is also influenced by the arrangement and placement of furniture inside the building.

In addition, [5] also concluded that the wavelength of a vibration also correlates with the size of the building that which is an important aspect of the soil-structure interaction. The vibrations would produce a translational motion to the structure if the width of the building is shorter compared to the wavelength. Conversely, a shorter wavelength produces vibrations that could introduce a bending in a structure. Another aspect is the individual element of the framework and the natural frequencies of the building.

2.3 Review of Established Standard and Guidelines on Human Annoyance

There are several ways available to determine the magnitude of a vibration. Three most common ways to determine the magnitude of vibrations are by using the velocity (mm/s), displacement (mm) and the acceleration (mm/s^2) [6]. For the purpose of this study, the velocity (mm/s) was used as the values needed to be compared to the values used by the standard Malaysian guidelines. The standard guidelines use velocity as the magnitude of vibrations. A document by [7] which is the Guide to the Evaluation of Human Exposure to Vibration and Shock in Buildings (1 Hz to 80 Hz) (ISO 2631) summarizes the works of numerous researchers who suggested that humans are sensitive to particle velocity within the range of 8 – 80 Hz. This means that the same level of velocity within different discrete frequencies would elicit the same response, such as discomfort or detection. Human body is less sensitive to vibration below 8 Hz [8].

Malaysia also has its own standard which is the "The Planning Guidelines for Vibration Limits and Control in the Environment" published by Department of Environment (DOE) Malaysia [9]. The recommended limits of vibrations during construction stages (short term vibrations) and during operation stages (steady state vibrations) are stated in this guideline. Table 1 and Table 2 shows the recommended limits for annoyance and human response due to the ground vibrations for both situations.

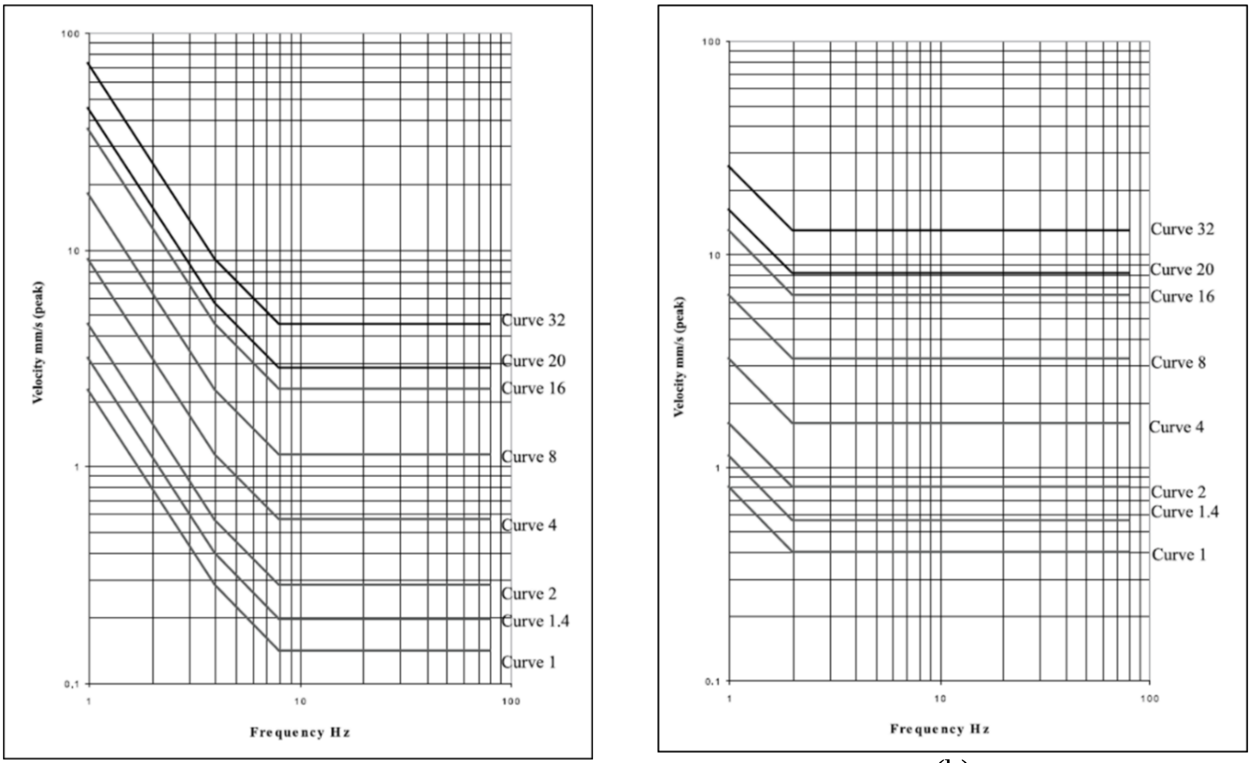
Table 1 - Recommended limits for human annoyance and response due to steady state vibrations [9]

Receiver: Land Use category	Day Time 7.00 am – 10.00 pm	Night Time 10.00 pm – 7.00 am
Vibration sensitive areas	Curve 1	Curve 1
Residential	Curve 2 to Curve 4	Curve 2
Commercial, Business	Curve 4 to Curve 8	Curve 4
Industrial	Curve 8 to Curve 16	Curve 8 to Curve 16

Table 2 - Recommended limits for human annoyance and response due to short term vibrations [9]

Receiver: Land Use category	Day Time 7.00 am – 10.00 pm	Night Time 10.00 pm – 7.00 am
Vibration sensitive areas	Curve 1	Curve 1
Residential	Curve 8 to Curve 16	Curve 4
Commercial, Business	Curve 16 to Curve 20	Curve 16 to Curve 20
Industrial	Curve 32	Curve 32

The stipulated which are curves based on the criteria indicated in Table 1 and Table 2 are shown in in Fig. 2. Curve is based on the perception threshold of vibration for human response as defined in the [7] and [10]. The subsequent curves numbers are based on the multiplying factors for the base curve [9].



(a) (b)

Fig. 2 - (a) Z- axis Curves of building vibration for peak velocity, (b) X & Y-axis of building vibration for peak velocity [9]

The Malaysian guidelines follow the requirement stated in [7] in which no adverse comment is expected either for acceleration or velocity values below the 1989 base curves in [7]. This standard uses combined-direction base curves in association with the multiplying factors by defining the acceptable level of vibrations in certain places or building as shown in Table 3.

Table 3 - Ranges of multiplying factors for vibrations with respect to human response according to ISO 2631-2 (1989) [9]

Area	Reaction	
	Day	Night
Workshop	8	
Office	4	
Residential	2 to 4	1.4
Critical working area	1	

In essence, the local guideline states that the limit of vibration is 4 mm/s which adopted the combined-direction base curves with multiplying factors. Comparisons between the Malaysian guidelines with the guidelines from other countries have shown significant difference. Based on the local standard, 0.567 mm/s from the z axis which is the vertical velocity is designated as the maximum limit of vibration towards human annoyance. The vertical velocity is the largest velocity obtained from the operating trains [11]. To determine the allowable limit of human response and annoyance using the local guidelines, human perceptibility thresholds of vibrations for a standing person by [12] was considered. The frequency (Hz) applied for velocity (mm/s) was in the range 10 Hz to 100 Hz. The same standard has been used in a report by [6] as well as many other researchers in exploring the the ground vibration induced by trains. This complements the research stating that humans are sensitive to particle velocity within 8 Hz to 80 Hz.

As conclusion, to determine the maximum allowable limit of human annoyance from the Malaysian standard, Z-axis curve was used with 8Hz as the minimum frequency and Curve 4 for residential areas criteria was determined. Using the criteria, the maximum limit of allowable vibrations velocity in Malaysia was obtained. Guidelines from most countries agree that the values approximately below 0.8 mm/s are considered to be the maximum limit of vibrations towards human response and annoyance. For commercial areas in Malaysia, the recommended limit for human response and annoyance is 1.176 mm/s which is higher than the residential areas. The summary of vibration limit among the countries can be referred in Table 4. Since this study focused on the residential areas, the limits were selected based on the human response in residential areas.

Table 4 - Different limit of vibrations for residential among the countries

Country/Standard	Vibration limits (mm/s)
The International Standards Organization [7]	0.2032
United State [8]	0.2540
Norway [13]	0.6000
Sweden [8]	0.4000
California [14]	0.3048
The Netherlands [15]	0.8000
Malaysia [9]	0.5670

2.4 Railway Traffic System in Malaysia

The railway system in Malaysia is a significant by-product of the industrial revolution and plays a major part in the economic and social development. Railway system in Malaysia is developed as a private public utility, serving dual purposes which are earning a profit to the owner and, at the same time, providing social service in the form of an affordable mode of transportation for both personal mobility and the transportation of their goods [16]. The first railway system in Malaysia was opened in 1885. At the time, Malaysia was known as Malaya. The railway connected Taiping to Port Weld with a distance of only 12 km. The railway tracks constructed were of the metre-gauge type which became the basis of the development of all the subsequent lines in Malaya. Presently, there is an extensive rail network serving most parts of the mainland of Malaysia. In addition to this, there are also cross-border railway lines that connect Malaysia and Thailand as well as Malaysia and Singapore [17].

In 1995, Malaysia has introduced a rail-based transit system in Kuala Lumpur known as the Keretapi Tanah Melayu Berhad (KTMB) which is owned by the Malaysia Rail Asset (MRA). With the Shared Prosperity Visions 2030 mission by the Malaysian government, Kuala Lumpur is now experiencing a rapid development in the rail-based transit infrastructure. Kuala Lumpur now has an inter-connected railway lines such as the Ampang Line (formerly known as PUTRA LRT), Kelana Jaya Line (formerly known as STAR LRT), KL Monorail, KLIA Transit, KLIA Express and Mass Rapid Train (MRT). LRT is owned by Prasarana Malaysia Bhd while MRT is operated by the MRT Corporation. Malaysia is also planning to develop high-speed rail systems to widen the coverage of the transit system [18]. Fig. 3

displays the Klang Valley integrated rail system that serves the area of Kuala Lumpur in 2014 while Fig. 4 shows the Klang Valley integrated rail system in 2020.

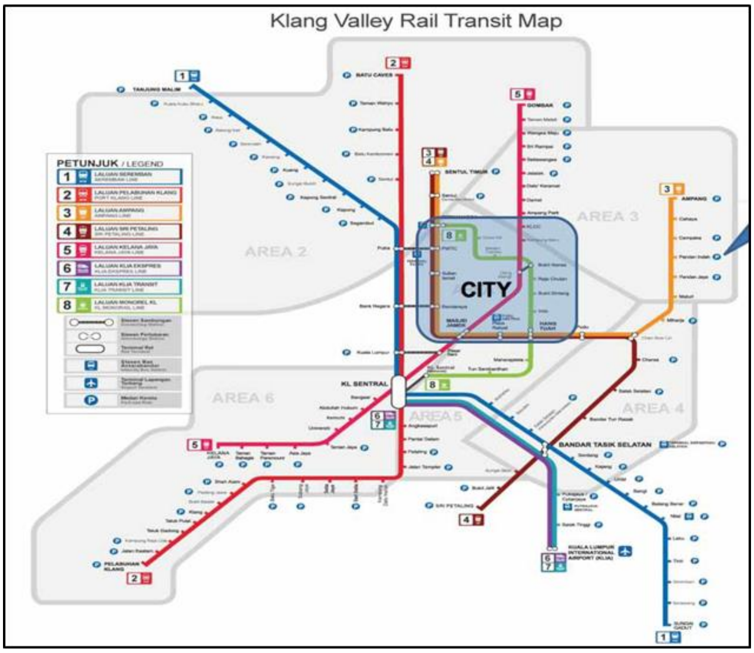


Fig. 3 - Klang Valley integrated rail system during 2014 [18].

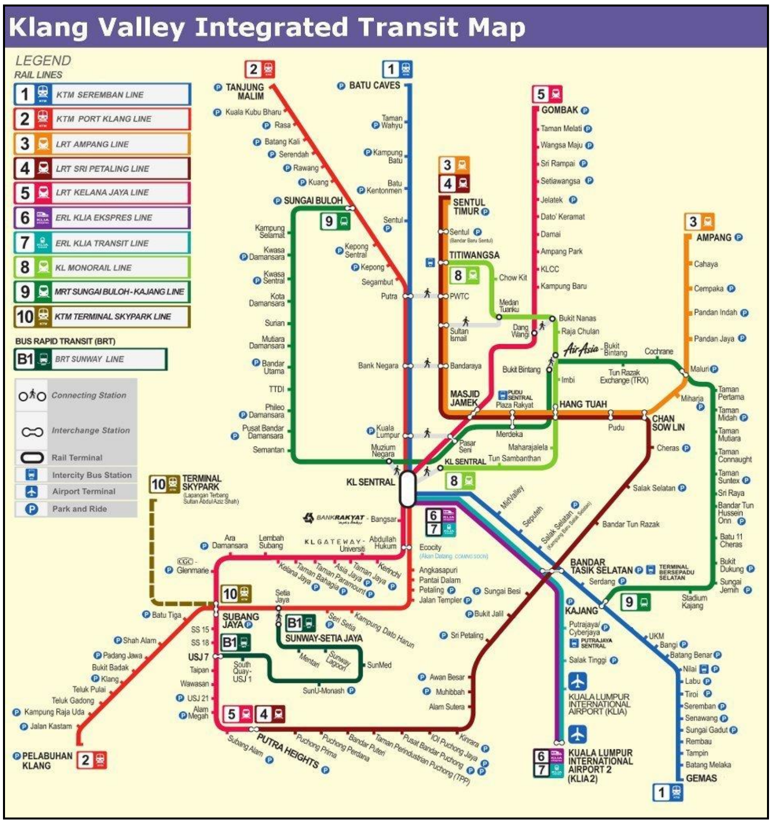


Fig. 4 - Klang Valley Integrated Rail System in 2020 [19]

Fig. 3 and Fig. 4 clearly show the rapid expansion of the rail transit system in Kuala Lumpur within six years. Line owners such as the Prasarana Malaysia Bhd and KTMB have also upgraded their trains to improve their services and provide better comfort to the passenger [20]. Table 5 shows the upgraded version of the trains by the Malaysian rail service owners.

Table 5 - Upgraded version of trains by Malaysian rail services

No.	Services	Old version train	New version train
1.	KTMB Line		
2.	KTMB Intercity Line		
3.	LRT Kelana Jaya Line		
4.	LRT Ampang Line		
5.	KL Monorail		

In Malaysia, rail transportation system consists of the light rail transit (LRT), heavy rail which includes the high-speed rail, the monorail and a funicular rail line. Heavy rail is mainly used for intercity passenger transportation and freight transportation as well as some urban public rail transport. The LRTs are used for urban public rail transport and other special uses such as the transportation of passengers between airports building. There is currently one high speed rail line with two high speed train services linking Kuala Lumpur city centre to the Kuala Lumpur International Airport knowns as the Express Rail Link or the ERL network. The country's sole monorail line is also used in Kuala Lumpur for public transport, while the only funicular railway line is located in Penang [16]. The completion of the MRT has improved the coverage of the railway system in Malaysia by connecting suburban areas in the Klang Valley. It is also an effort by the government to reduce road traffic congestion in the Klang Valley by increasing the railway transit users. The expansion of the railway transportation in Malaysia is not only limited in the areas within the Klang Valley. The Malaysian government in its masterplan has already proposed for the improvement of the railway system which will cover other states in the country. Table 6 shows the Malaysian railway projects that are in proposal stage, construction stage and the completed projects.

Table 6 - Malaysia railway project

No.	Owner	Train Services	Status of Project	Project Cost (RM)
1	Mass Rapid Transit (MRT) Corp	MRT 1: Sungai Buloh – Kajang Line [21]	Completed	21 Billion
		MRT 2: Serdang – Sungai Buloh – Kajang Line [22]	In Progress	30.53 Billion
		MRT 3: Circle Line [23]	In Progress	20 Billion
		The Johor Bahru – Singapore Rapid Transit System [24]	In Progress	10 Billion
2	Prasarana Malaysia Berhad	Rapid Rail Sdn Bhd (Subsidiary of Prasarana Malaysia Berhad) 1. LRT Ampang Line [25] 2. LRT Kelana Jaya Line [25] 3. Monorail Line [26]	 Completed Completed Completed	 3.24 Billion 5.38 Billion 1.18 Billion
		LRT 3 [27]	In Progress	16.63 Billion
3	Malaysia Railway Asset (MRA)	Keretapi Tanah Melayu Berhad (KTMB)	Completed	N/A
		Gemas – Johor Bahru electrified double tracking [28]	In progress	8.9 Billion
		Ipoh – Padang Besar northern double track [29]	Completed	13 Billion
4	High Speed Rail (HSR) Corp	High Speed Rail from Kuala Lumpur, Malaysia to Singapore [30]	In Progress	43 Billion
5	Malaysia Railway Link (MRL)	East Cost Railway Link (ECRL) [31]	In Progress	44 Billion
6	Express Rail Link Sdn. Bhd.	KLIA Transit [32]	Completed	2.4 Billion
7	Sarawak Metro	Sarawak's ART public transportation system [33]	In Progress	5 Billion
		Line 1: Kota Samarahan to Sungai Baru [33]	In progress	10.8 Billion
		Line 2: Serian to Senari [33]	In Progress	
		Line 3: City Dispersal Line [33]	In Progress	
8	Suruhan Jaya Pengangkutan Awam Darat (SPAD)	Tram service: Putrajaya – Cyberjaya – Bangi – Kajang [34]	Proposal Stage	N/A
9	Putrajaya Corporation (PjC)	Monorail project [35]	Proposal Stage	N/A
10	Penang State Government	Penang LRT [36]	Proposal Stage	8 Billion
11	Viral Rail Lines (VIRAL) Bhd.	Melaka to KLIA electric train [37]	Proposal Stage	12 Billion
12	Sabah Infrastructure Development Ministry	Kota Kinabalu to Kudat rail [38]	Proposal Stage	5.2 Billion

The summary of the railway project as shown in Table 6 proves that the government is trying to aggressively improve the rail transit system and this involves a large amount of investment. The total costs for all of the projects exceed RM 1 Billion. With the extensive plan for the expansion of the rail transit systems in Malaysia, studies on prediction of vibrations within the nearby residential areas are vital to ensure that vibration mitigation measures can be planned and executed to improve the quality of life of the affected population. Future projects such as the East Coast Railway Link (ECRL) which connects different states in Malaysia and the Kuala Lumpur – Singapore High-Speed Rail should be effectively investigated to mitigate the effect of the ground-borne vibration. This is because the railway tracks are expected to be passing through residential areas across the country.

As the future inter-state railway tracks will run along through some strips of residential areas and will be constructed on the ground level, it is important for the relevant parties to investigate and predict the ground vibrations which may result in unpleasant human response such as annoyance and discomfort. Due to this foreseeable condition, the KTMB line has been chosen for this research as the KTMB rail tracks are also of the above-ground type and pass through many residential areas. In addition, the rail tracks are not only used for passenger train but also for freight trains.

The commuter trains and Electric Train Services (ETS) operated by the KTMB produce lower noise level compared to the diesel train. Diesel locomotive is the oldest train used by the KTMB either for intercity passenger services or cargo services. All KTMB locomotive trains are of diesel type. Diesel locomotive either freight or passenger locomotive normally produces high noise level and at the same time tends to induce larger ground vibrations. The first electric train services in Malaysia was introduced by the KTMB in 1995. The electrified double-track railway services were initially used for commuter trains that primarily link the suburban areas and the city centre. In a study by [39], the research has derived that the electrically powered KTMB commuter trains produced lower noise level compared to the diesel KTM locomotives. Table 7 shows the comparison of percentages difference between the noise level and permissible noise level based on the guideline from DOE.

Table 7 - Percentage difference by different types of train by [39]

Type of trains	Noise levels measured	Permissible noise level	Percentage of difference (%)
Freight train	93.9	65	44.46
Locomotive Diesel Train	93.9	65	44.46
KTM Commuter	79.9	70	14.14
Electric Train Service (ETS)	72.2	70	3.14

As observed in Table 7, despite the advancement of the railway technology such as the use of electrified track network, the reduction in noise level still did not meet the guideline stated by the DOE. Besides, the noise level measured for the ETS also exceeded the permissible noise level. It can be deduced that the guidelines proposed by the authority might have not been seriously considered during the planning stage or construction of the railway projects.

3. Methodology

3.1 Case Study

This research was conducted along the KTMB railway track Padang Jawa, Shah Alam to Klang, Selangor. The railway track under study is a double-track railway involving two (2) directions of trains; one heading to Kuala Lumpur and another to Pelabuhan Klang, Selangor. This research covered nine (9) different sites located along Padang Jawa Station, Shah Alam to Klang Station, Klang. These locations were selected to distinguish the variety of vibration magnitude induced by the trains running on the railway tracks. The locations were chosen due to the strategic areas as there were numerous residential areas along the track that have been affected by the occurrence of the ground-borne vibration. This research also focused on areas with landed type residential buildings. Fig. 5 shows the map of locations of study in Padang Jawa Station, Shah Alam until Klang Station, Klang.

The route has been chosen due to the existence of landed residential buildings in the areas just beside the railway tracks. There were no vibrations barriers located along the sites that have been chosen. The range of the distance from the residential area to the rail tracks for this study was less than 30 meters. Field data collected during the site survey were train parameters such as the type of trains, the speed of the trains and the time condition which was either during peak hour or non-peak hour. Another set of data collection was the ground -borne vibration measurements which consisted of the vertical wave vibration, horizontal and radial wave vibrations. These measurements were obtained using a seismograph installed at the site under study. As for the site locations, three sites were chosen from Padang Jawa station to Bukit Badak Station. The other six sites that have been chosen were located between Bukit Badak Station to Klang Station. The sites were chosen to be as close as possible to the landed residential areas. Different locations were selected in order to obtain various speeds of the trains and various distances from the residential areas to the sources. Shah Alam and Klang are one of the most developed and have the highest population in Malaysia.

3.2 Instrumentation and Equipment Strategy Setting Up

For this study, five repetitions of data reading and measurements were conducted for each site location using a seismograph meter or also known as the MiniSEIS. The data were recorded and grouped into two classifications;

during peak hour and non-peak hour at two different distances at each site location. This was carried out due to an assumption that the load carried by the trains would be different between peak hour and non-peak hour as the volumes of passenger during peak hour were expected to be higher. Detail illustrations showing the location of the Mini-SEIS placement are demonstrated in Fig. 6 and Fig. 7. For the experiments conducted in the morning, two sessions of data collection have been carried out with two hours of experiment for each session. This was to collect the peak and non-peak hour session data. Another two sessions were conducted in the evening to collect the peak and non-peak hour data from different distance locations of the Mini-SEIS from the sources. Midnight sessions were conducted for another two hours to obtain the data from freight train since freight train only operates after passenger commuter operation ends. Table 8 below shows the timeline of the data collection. The locations of the Mini-SEIS are demonstrated in Fig. 6 and Fig. 7.

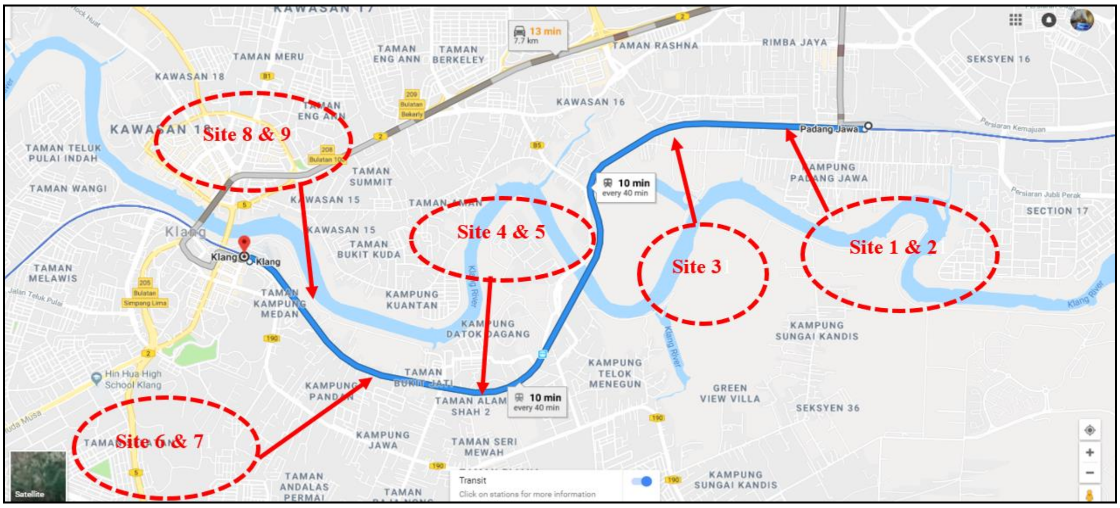


Fig. 5 - Maps of nine site study located in Padang Jawa until Klang, Selangor

Table 8 - Timeline of data collection based on location of Mini-SEIS

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
2.00 am – 4.00am (**Midnight**)		1 = d1 & d2	Freight

Note: Location of mini-SEIS 1 & 2 and distance d1,d2,d3 and d4 refer to Fig.15 and Fig. 16.

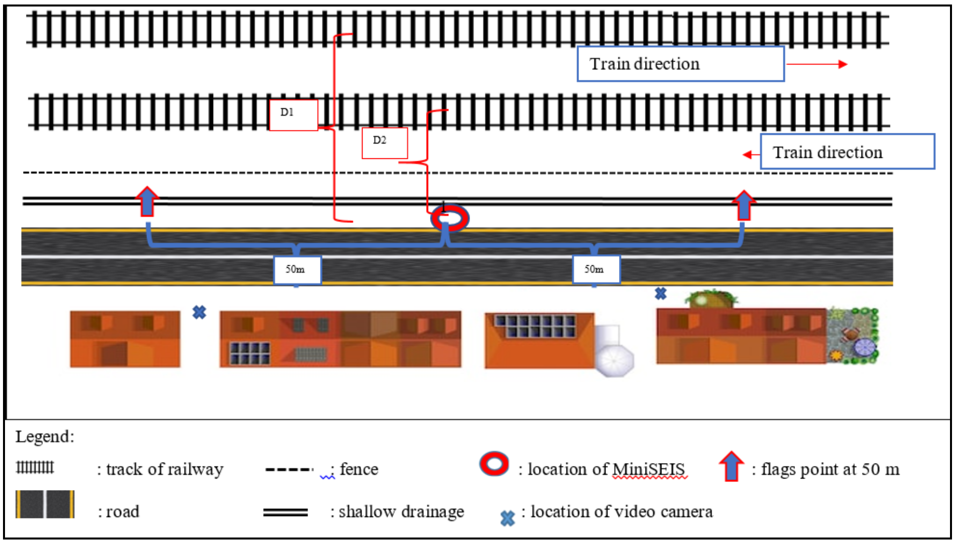


Fig. 6 - The location of mini-SEIS at location 1 for morning session and midnight session of each site locations

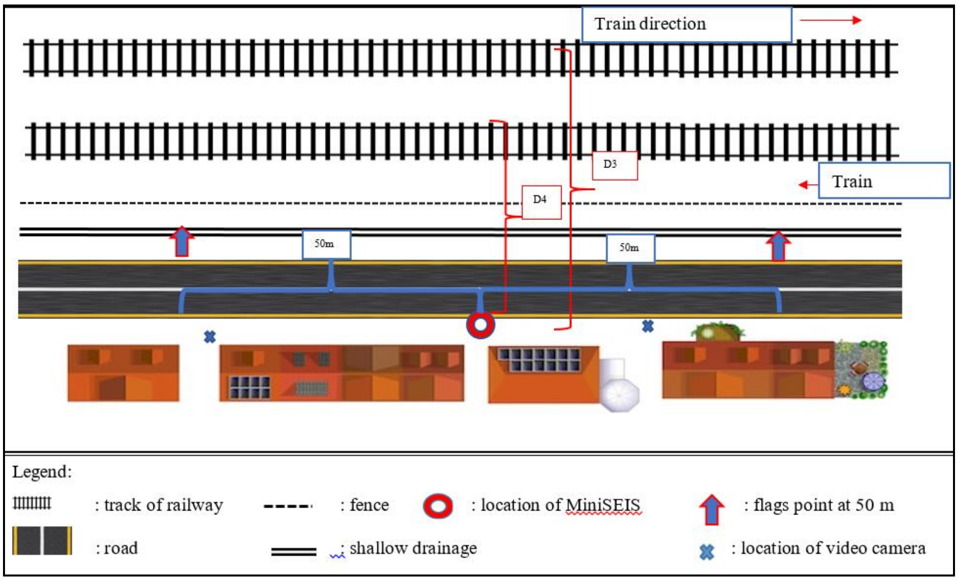


Fig.7 - The location of mini-SEIS at location 2 during evening session of each site locations

The Mini-SEIS was installed outside the KTMB fencing gate of the railway tracks. Fig. 8 shows the installation of the Mini-SEIS at the site of study.

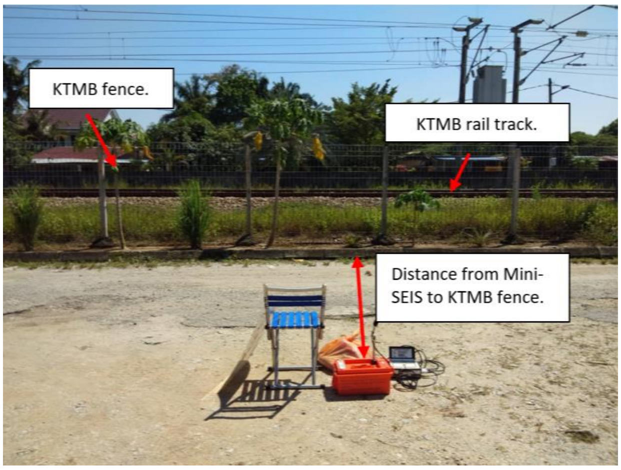


Fig. 8 - Installation of mini-SEIS at study area

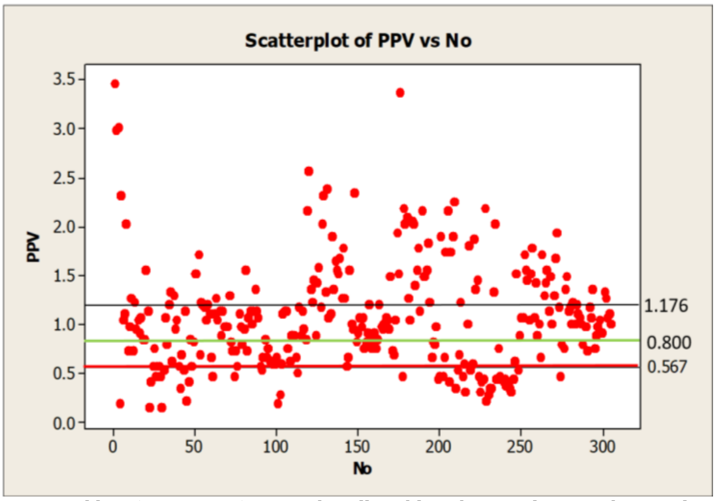
The Mini-SEIS was placed within the range of 25 metres from the rail track. This range of distance was deemed to be sufficient for this study as there are houses located within this range, making the evaluation of human annoyance caused by the vibration to be possible.

4. Data Analysis

Mini-SEIS produced the peak particle velocity which was obtained from the traverse, radial and horizontal direction of the ground-borne vibration. However, only the vertical direction of the vibration was analysed since it recorded the highest number of vibrations detected from the Mini-SEIS. In their research, [40] and [41] also mentioned that the vertical velocity has the largest wave for a ground-borne vibration. From the data collected in this study, out of the 772 data of vibrations velocity obtained, 649 data were recorded from the vertical directions as peak particle velocity (PPV) which was 85% the total data recorded.

4.1 Threshold Limit for Allowable Limit Based on Malaysian Standard

Fig. 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 DOE.



Note: Red line (0.567 mm/s) is the allowable vibration limit with regard to human annoyance level set by the Malaysian authority in residential areas. Green line (0.8 mm/s) is the average allowable vibration limit of human annoyance based on other countries. Black line (1.176 mm/s) is the allowable vibration limit of human annoyance level set by Malaysian authority in commercial areas.

Fig. 9 - Scatterplot of PPV comparison with the allowable limit set by the authority guideline

The recommended limits for human annoyance set by the authority guideline with regard to the steady state vibrations is 0.567 mm/s for residential areas. From the result in Fig. 9, the values of most of the vibrations induced by the train travelling along the sites under study were more than the allowable vibration limit. The vibration values obtained were even higher than the recommended vibration limit for commercial areas taken from the similar guideline which was 1.176 mm/s. All other international standards states that the allowable of vibrations limit with regard to human annoyance should not be 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 sites of study have exceeded the recommended limit for commercial areas despite being residential areas. This contributed to higher perception of annoyance among the residents of the affected areas. Similar trend of results were also obtained by most of the researchers such as [42] from United States and [43] 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.

4.2 Fundamental of Rail Traffic Vibrations

Scatterplot of the significant variables was computed to evaluate the relationship between the variables with the peak particle velocity induced by railway traffics. Fig. 10 shows the scatterplot of PPV versus the speed of train.

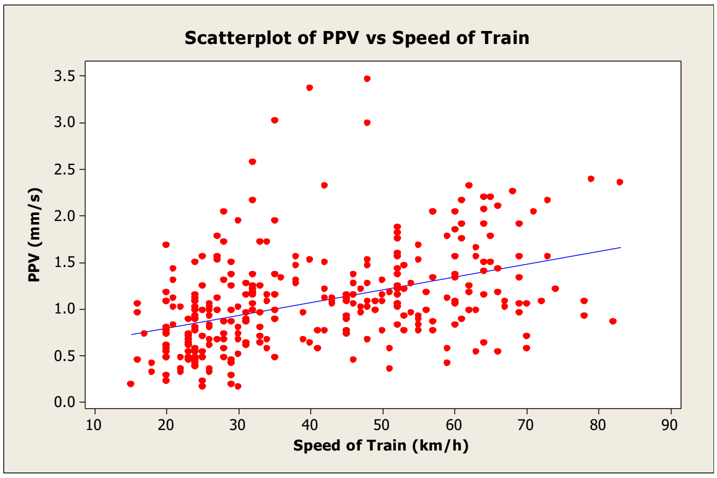


Fig. 10 - Scatterplot of PPV (mm/s) versus speed of train (km/h)

From Fig. 10, the ratio of the PPV measured in mm/s and the train speed (km/h) was proportional to a positive slope. Thus, it can be deduced that as the train speed increased, the PPV values have also increased. This scatterplot was solely based on two dimensional axes, distributed randomly without considering the distance between the sources and receivers and also without considering the type of train. With these results, the hypothesis of this study was acceptable as it was observed that the higher the train speed, the bigger magnitude of ground vibration was produced.

Based on the findings, the distance of the source of vibration to the receiver has a major influence on the magnitude of the ground-borne vibration. The nearer the receivers to the source, the higher vibrations velocity was induced. The statement was proved and agreed by [40] which stated that as the distance from the track increases, the levels of vertical vibration would decrease. For this study, the range of distance of the receiver to the source was limited to below than 25 meter. Fig. 11 shows the scatterplot of PPV in mm/s versus the distance (m) of source of vibration to the receivers.

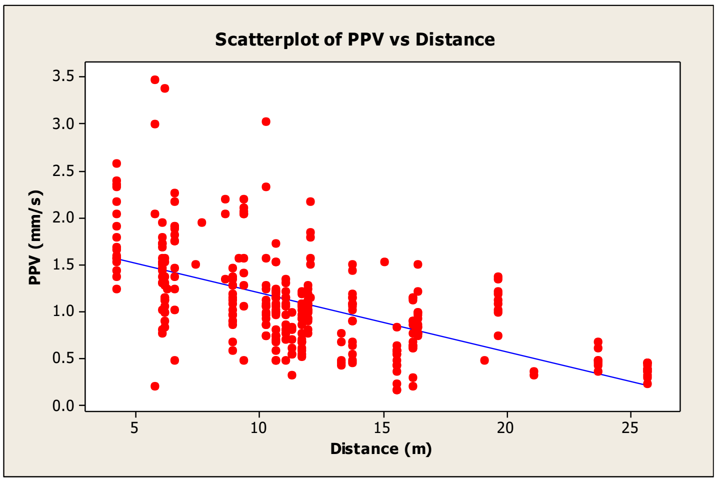
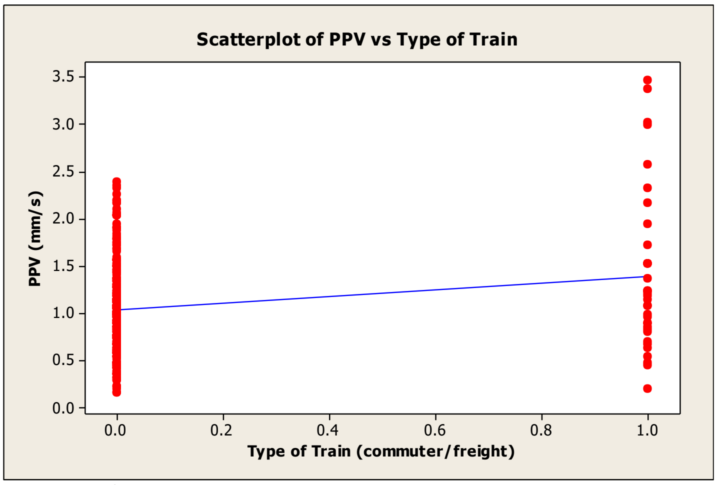


Fig. 11 - Scatterplot of PPV versus distance

The PPV versus distance is linear with a negative slope which proved that the longer the distance of receiver to the source, the lower the particle peak velocity produced. Another hypothesis based on this study was that the freight train tended to produce higher ground borne vibrations compared to the commuter train. Fig. 12 shows the scatterplot of the PPV versus the types of train.



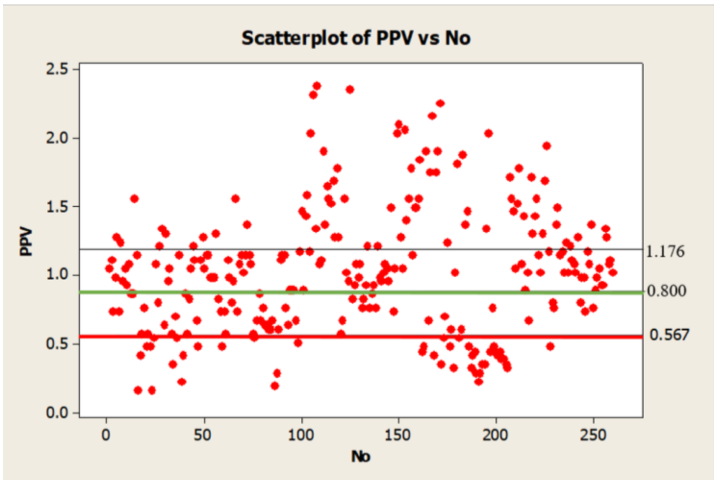
Note: Type of Train, 0 = Commuter, 1 = Freight

Fig. 12 - Scatterplot of PPV (mm/s) versus type of train

From Fig. 12, freight train which was indicated as “1” recorded higher ground-borne velocity vibrations compared to the commuter train which was indicated as “0”. A research by [44] also found that ground borne vibration induced by freight train was higher than commuter train.

4.3 Threshold Limit for Allowable Limit for Commuter Train

Fig. 13 shows the comparison scatterplot of the peak particle velocity of the commuter train with the allowable limit of vibration based on the local authority guidelines.



Note: Red line (0.567 mm/s) is the allowable vibration limit of human annoyance from the DOE guideline in residential areas. Green line (0.8 mm/s) is the average allowable vibration limit of human annoyance from other countries. Black line (1.176 mm/s) is the allowable vibration limit of human annoyance from the DOE guideline in commercial areas.

Fig. 13 - Scatterplot of PPV commuter comparison with allowable limit set by the authority guideline

The recommended limit for human annoyance and response for stable state vibrations which have been specified by the DOE is 0.567 mm/s, applicable at residential areas. From the result in Fig. 13, it showed that most of the vibrations caused by the train along the sites of study were recorded to be more than the permissible vibration limit specified. Furthermore, when compared with the recommended vibration level of 1.176 mm/s for the commercial region, the results also indicated that there were vibration values that have exceeded the recommended limit. All international guidelines agree that the maximum acceptable limit of human irritation caused by vibrations is 0.8 mm/s. This indicates that as the vibrations from the commuter train reach and exceed the acceptable limit, the subsequent vibrations would be perceived as irritation by the residents in the nearby residential areas. The results of this study indicated that the vibrations caused by commuter train travelling along the designated sites have exceeded the recommended human annoyance limit. Moreover, the vibrations measured have also surpassed the recommended level in commercial areas. These results were not surprising as similar trend of findings have been revealed based on a study performed in Japan. In their study, [45] found that the ground-borne vibrations induced by the railway traffic in Japan also resulted in human annoyance in the affected area.

4.4 Fundamental of Commuter Rail Traffic Vibrations

From Fig. 14, the trend of the PPV quantified in mm/s and speed of trains (km/h) shows a linear trend with positive sloping which indicated that as the speed of trains increased, the PPV have also increased. This scatterplot was solely based on two-dimensional parameters with random scatters without considering the distance of the source to the receiver. This correlation was also proved by [46] and [47] in their research which found that higher speed of the trains would result in higher level of vibrations. This analysis led to the acceptance of the hypothesis which stated that higher speed of trains would produce higher ground-borne vibration.

The distance of the source of vibration to the receiver has also significantly affected the ground-borne vibration. The nearer the receivers to the sources, the higher vibrations velocity were recorded. This statement had been proved and agreed by [48] who found that as the distance from the track increase, the levels of vertical vibration tend to decrease. For this study, the distance of receiver to the source has been capped to below 25 meters. Fig. 15 shows the scatterplot of the PPV in mm/s versus the distance (m) between the source of vibration to the receiver.

The plot for PPV against the distance shows a linear trend with a negative slope indicating that the longer the distance between the receiver and the source, the lower the particle peak velocity produced. This result was also similar to the findings made by [2], [46], [48] and [49] in their research. The hypothesis which stated that the further the distance of the receiver to source, the lower the ground-borne vibration produced was consequently acceptable.

4.5 Threshold Limit for Allowable Limit for Freight Train

As explained in the earlier analysis of the commuter train, the recommended limit for tolerable human annoyance and response in a steady state vibration is 0.567 mm/s for residential areas as stated in the guideline by the Malaysian DOE. This standard is also applicable for freight trains. Fig. 16 shows the data tabulation of the PPV induced by freight train that have been derived from the filed study data

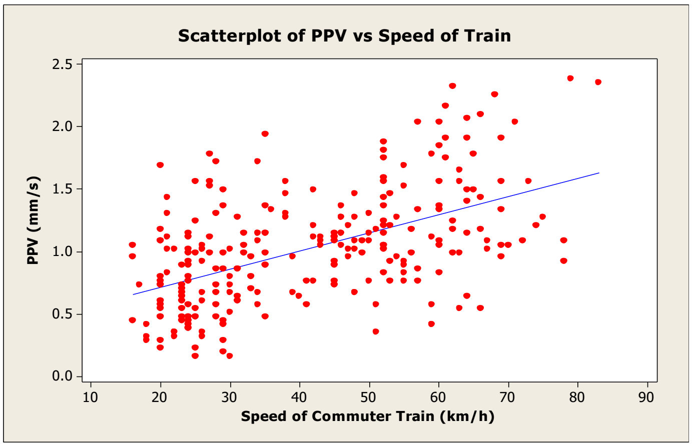


Fig. 14 - Scatterplot of PPV (mm/s) versus speed of commuter train (km/h)

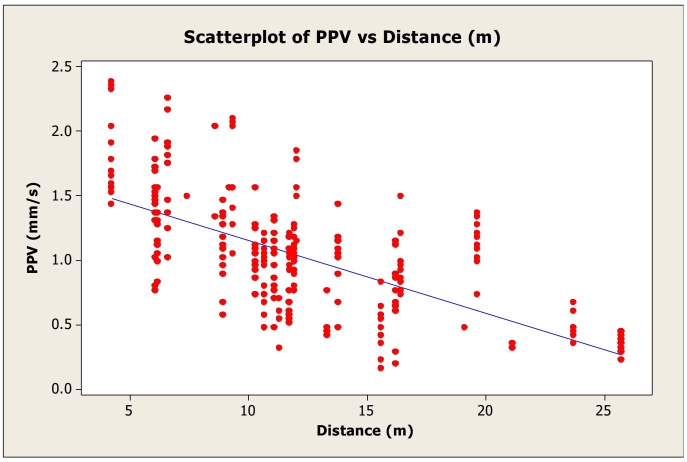
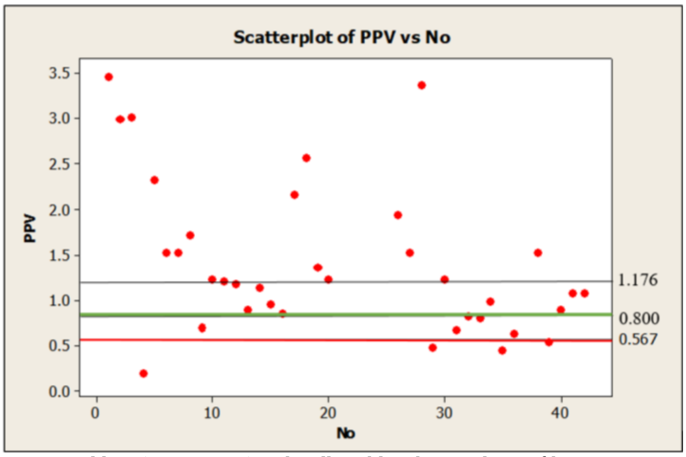


Fig. 15 - Scatterplot of PPV (mm/s) versus distance (m)



Note: Red line (0.567 mm/s) is the allowable vibration limit of human annoyance level set by the Malaysian authority in residential area. Green line (0.8 mm/s) is the average allowable vibration limit of human annoyance from other countries. Black line (1.176 mm/s) is the allowable vibration limit of human annoyance annoyance level set by the Malaysian authority in commercial area.

Fig. 16 - Scatterplot of comparison between PPV from freight train with the allowable limit set by the local authority

From the results in Fig. 16, it shows that most of the vibrations induced by the freight trains along the sites of study exceeded the allowable vibration limit stated in the standard guidelines. The vibration values obtained were even higher than the recommended vibration limit for commercial areas taken from the similar guideline which was 1.176

mm/s. The results also showed that the vibrations values tended to surpass the allowable limit for human annoyance set by international standards which is 0.8 mm/s. This signified that the vibrations from the freight trains have exceeded the allowable limit and the vibrations have created a certain level of irritation among the residents in the affected areas. The results also revealed that the vibrations induced by the freight trains have even exceeded the recommended level in commercial areas based on human annoyance perception. This pattern was expected earlier during the analysis of the commuter train results. However, the ground-borne vibrations produced by freight trains are higher than the ones produced by commuter trains [4], [44].

4.6 Fundamental of Freight Rail Traffic Vibrations

In Fig. 17, it can be seen that the trend of the particle peak velocity (PPV), measured in mm/s and the speed of freight trains (km/h) was linear with a positive slope. As the speed of freight trains increased, the PPV have also increased. This scatterplot was based solely on two-dimensional parameters with random scatter without considering the distance of the source to the receiver. [2] and [43] also agreed on the statement that the freight trains produce higher vibrations if the speed is higher.

Ground-borne vibrations induced by freight trains were expected to be higher if the receivers were located nearer to the sources which were the railway tracks. When the residential building is close enough to the track, the vibrations especially induced by the freight trains would be strong enough for the residents to notice it [50]. The statement was also proved and agreed by [40] who found that as the distance from the track increased, the levels of vertical vibration decreased. For this study, the distance of the receiver to the source was limited to less than 25 meter. Fig. 18 shows the scatterplot of PPV measure in mm/s versus the distance (m) of the sources vibration to the receivers.

The plot of the PPV against the distance has a linear with a negative trend which proved that the longer the distance of the receivers to the sources, the lower the particle peak velocity produced. The hypothesis regarding the distance between the receivers and the sources was consequently acceptable.

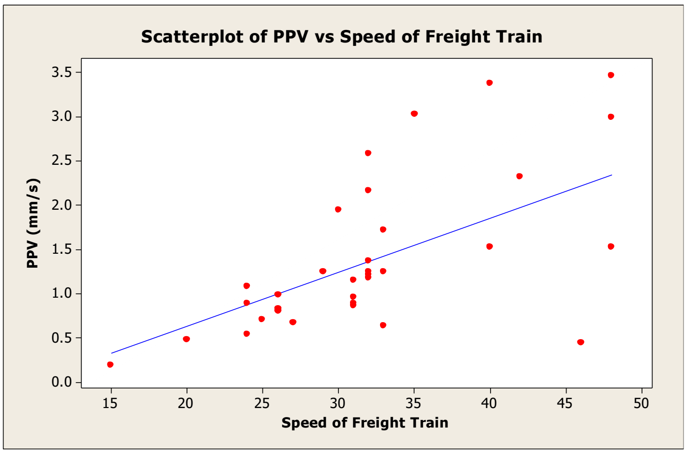


Fig. 17 - Scatterplot of PPV (mm/s) versus speed of freight train (km/h)

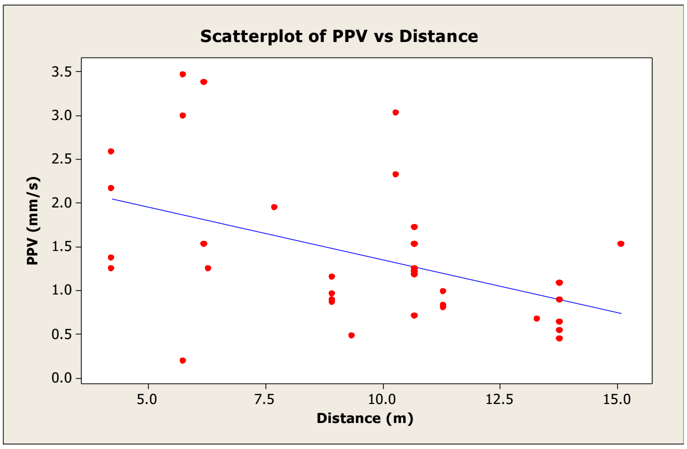


Fig. 18 - Scatterplot of PPV (mm/s) versus distance (m) of sources of vibration to the receivers

5. Conclusion

The stage of evaluating the ground-borne vibrations against the human response and annoyance at residential area involved comparisons between the obtained data with the guidelines fixed by the authority regarding the vibration limit. This study managed to show that the obtained field data have exceeded the allowable limit of vibrations. Freight train was found to produce even higher vibration. This indicated that the residents from the nearby areas have been experiencing poor quality of lives due to the ground-borne vibration induced by the trains. This may affect the general health and well-being of the residents such sleep disturbance that could cause mental health issue. However, as explained by the previous researchers, the issues tended to be dismissed by the residents as they claimed that they are already accustomed to the problems. The relevant authority should actively solve the problem so that the quality of lives among the residents living nearby train track could be improved by minimising the level of the ground-borne vibration induced by the passing trains. Solutions such as vibration barriers or vibrations absorber should be implemented at the perimeter of the tracks and the residential areas. As stated in the code of practice by the Malaysian Standard, the implementation of isolation materials or vibration attenuating or structural breaks are required if the vibrations exceed the maximum recommended limits if buffer zone is not possible. It is recommended to use tracks vibration isolation such as ballast mats, floating track slabs, resilient track fasteners and undersleeper pad.

Acknowledgement

The authors would like to thank the authorities from the Faculty of Civil Engineering, Universiti Teknologi MARA (UiTM) for their constant support and encouragement. Appreciation goes to the Research Management Institute (RMI, UiTM) and Ministry of Higher Education Malaysia (MOHE) for the financial supports FRGS Grant scheme: RMI File No: 600-IRMI/FRGS 5/3 (008/2019), Sponsorship File No: FRGS/1/2018/SKK06/UITM/02/5.

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