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Investigations on transportation induced ground vibrations

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Abstract

The paper describes measurements of train and traffic induced ground vibrations. Vibration impacts relate to annoyance and potential for structure damage. Buildings in vicinity of mass transit projects respond to these vibrations with varying results ranging from perceptible effects, low frequency rumbling sounds and even slight cosmetic damage to structure. Thus, it is imperative to ascertain the amplitude of vibrations generated due to train and traffic for characterizing the ground borne noise radiated due to it and possible mitigation measures to be adopted either at the path or receiver ends, if source can't be diagnosed. The present work discusses the measurements of vibration amplitude generated due to traffic and trains at grade and underground metro trains and correlate them with the various damage criteria for building elements.

1. Introduction

The environmental impact of vibrations induced by road traffic is in increasing concern in modern world especially amongst the residential areas. With the introduction of mass rapid transit systems, although the transportation facilities have much improved, yet their operation may result in an additional impact on the buildings and residents living nearby. Thus, it is indispensable to conduct the noise and vibration impact studies to assess the relative impact of the means of transportation to avoid any damage to nearby buildings and take precautionary measures for combating with it. Modern buildings have lower inherent damping and lower vibration frequencies as compared to older ones due to increasing use of lighter and stronger materials and construction of more tall buildings, which makes them more susceptible to ground borne vibrations [1]. There are various international codes and damage criteria developed by researchers in terms of peak particle velocity for investigating the onset of building damage in case vibration level exceeds a limiting value. ISO defines that PPV less than 0.3 mm/s is imperceptible and above 3 mm/s is disturbing and annoying irrespective of the vibration frequency [2]. Rudder had also suggested a threshold level for building damage as 2.5 mm/s (ppv) [3]. For old and historic buildings the German Standard DIN 4150 [4] recommends a maximum velocity of 2 mm/s. The Swedish Environmental Protection agency [5] have suggested a particle velocity of 0.4 mm/s (rms) and particle acceleration of 14 mm/s^2 (rms) for frequency range 1-80 Hz as ground borne impact criteria. The Danish Environmental Protection Agency recommends weighted acceleration value of 5.6 mm/s^2 and weighted velocity of 0.16 mm/s for residential areas, and a higher value of 10 mm/s^2 and weighted velocity of 0.3 mm/s for dwellings in day use and offices [6].

Vibration induced by road traffic is common concern in the metro cities. The alarming increase in vehicular density on roads has not only created annoyance but also more susceptibility of building damage. The literature reveals that modeling of traffic and train induced vibrations and validation with the actual levels has been reported by many researchers, but due to complexity of the problem and uncertainties involved in measurement of input parameters, the actual results sometimes differ from that of predicted ones. TRL [7, 8] formulated a prediction model in terms of PPV as:

$$PPV\ (mm/s) = 0.028\ a\ (v/48)tp\ (r/6)^x \qquad [1]$$

where a is the maximum height or depth of a localized surface irregularity (mm), v is the maximum expected speed of heavy vehicle (km/h), t is the ground scaling factor; p the wheel track index for heavy vehicle equal to 0.75 if the irregularity only involves one wheel path, otherwise equal to 1; r is the distance between irregularity and building foundation (m); x the exponent of power that defines the damping of vibration with distance. The values of t and x are dependent upon the soil conditions. A study of traffic induced vibrations and effect to old masonary buildings have been initiated in European nations (Watts 1990; Atkinson et al. 1998; Crispino and D'Apuzzo 2001; Kliukas et al. 2008). Crispino [9] conducted measurements of road traffic in a heritage building in Naples and concluded that ISO 2631 perception threshold for PPV (0.14 mm/s) was exceeded in all acquired data and in some cases vibration level exceeded the lowest damage PPV threshold found in literature (1 mm/s). Hao measured traffic induced ground vibrations at four sites at a distance of 20 m from the road centre. Road traffic tends to produce vibrations with frequencies predominantly in the range from 5 to 25 Hz [10]. The amplitude of the vibrations ranges between 0.005 and 2 m/s^2 measured as acceleration, or 0.05 and 25 mm/s measured as velocity [10]. The predominant frequencies and amplitude of the vibration depend on many factors including the condition of the road; vehicle weight, speed and suspension system; soil type and stratification; season of the year; distance from the road; and type of building. The effects of these factors are interdependent and it is difficult to specify simple relationships between them

The amplitude of train vibrations depends upon vehicle characteristics, rail and wheel roughness, speed, characteristics of rolling stock and dynamic soil characteristics. Spectra of railway-induced ground vibrations, including train-speed dependent components, have been studied experimentally and analytically by several authors [11-13]. Vibrations from trains can cause annoyance to people as well as damage to the nearby buildings. The maximum level of vibration is highly dependent on train weight as well as train speed. Hall [14] numerically analyzed the train induced vibrations and concluded that three dimensional analyses are necessary to achieve a better simulation as compared to two dimensional models. Xia et al. [15] showed that the velocity response levels of the environmental ground and the building floors increase with train speed, and attenuate with the distance to the railway track. The research carried by Xie et al. revealed that in the multi-story building, the lateral velocity levels increase monotonically with floor elevation, while the vertical ones increase with floor elevation in a fluctuating manner. Yokoyama [16] discussed the induced ground vibration characteristics of Shinkansen traveling at speed of 300 km/h and found a very low frequency band of 4 Hz with some ground conditions as a dominant band. A lot of work reported in literature so far attempted for modeling and measuring the train induced vibrations reveals that in some situations train vibration could prove harsh for building elements. Thus, not only diagnosing the source would suffice, but also focusing on mitigation measures in propagation path has also to be explored for combating train induced ground vibrations. Stabilization of the soft soils under the track by for example lime-cement columns is one of the methods that can be used for reducing the level of vibrations [17]. A promising and cost effective method of screening can be using heavy masses placed on the ground surface near the roads (e.g. concrete or stone blocks, specially designed brick walls, etc). When the mass is shaken under the impact of incident Rayleigh surface waves, it scatters the incident waves into the depth of the ground and at different directions on the surface, thus resulting in noticeable resonant attenuation of transmitted ground vibrations. Using suitable combinations of such mass scatterers, one can expect to achieve efficient vibro-isolation of affected buildings [18].

The present work reports limited in-situ measurements conducted to evaluate the amplitude and characteristics of vibration levels generated due to train and traffic transportation and correlate with the damage criteria for building elements.

2. Field measurements and analysis

The in-situ vibration measurements were carried out with the help of a calibrated vibration analyzer (Pimento Recorder P-4070 and Pimento FFT Analyzer P-4000) under existing environmental conditions. The seismic accelerometer (Dytran Model 3100D24 and B&K 8318 connected to a B&K measuring amplifier Type 2525) of the vibration analyzer was fixed on the vibrating surface with the help of stud on a steel rod embedded deep in the ground. A field study was conducted for monitoring the train induced ground vibrations at Chander Nagar Halt, Sahibabad and also in underground metro stations at Vidhan Sabha of Delhi Metro Rail Corporation. Table 1 summarizes the acceleration and velocity levels monitored at a distance of 4 m and 10 m from the track.

Table 1. Summary of instantaneous vibration measurements due to coming trains at Chander Nagar Halt, Sahibabad

Train Description	**Speed of Train (km/h)**	**Acceleration level (mm/s^2)**	**Velocity Level (μm/s)**	**Sound Pressure Level (L_{eq}) in dB (A) @ 1 m**
Puspak (NOB* = 21)	100	153 at 4m	392	94.3
Gomti (NOB=24)	82	148 at 4m	354	84.8
Sharamjivi (NOB= 24)	95	149 at 4m	376	87.9
Kasi Viswanath (NOB=25)	75	97 at 4m	258	88.4
Gomti (NOB=24)	80	109 at 4m	230	83.9
Reva (NOB=15)	83	107 at 4m	365	82.4
Jan Shatabdi (NOB=14)	70	65 at 10m	257	85.7
EMU (NOB=10)	55	63 at 10m	256	62.3
Mall train (NOB=42)	130	161 at10m	445	81.7
Swatantra Senani(NOB=24)	80	120 at 10m	305	88.2
Laxmi (NOB=16)	83	112 at 10m	361	81.8

* NOB is number of Bogies of train

Fig. 1 and 2 shows the acceleration and velocity spectrum of the train approaching at an average speed of 80 km/h at a distance of 4 m from the track. The frequency response of ground vibration with a characteristic peak at low frequencies attributed to resonance of wheel against the track. The peaks in the ground motion occur at axle passing frequencies. The vibration energy will then propagate as surface waves towards the wall and roof of buildings although some of them may be attenuated due to geometrical and material damping. The natural frequency of the building lies in a lower range of less than 10 Hz and if train induced vibrations are within the same domain, the resonance effects are prominent.

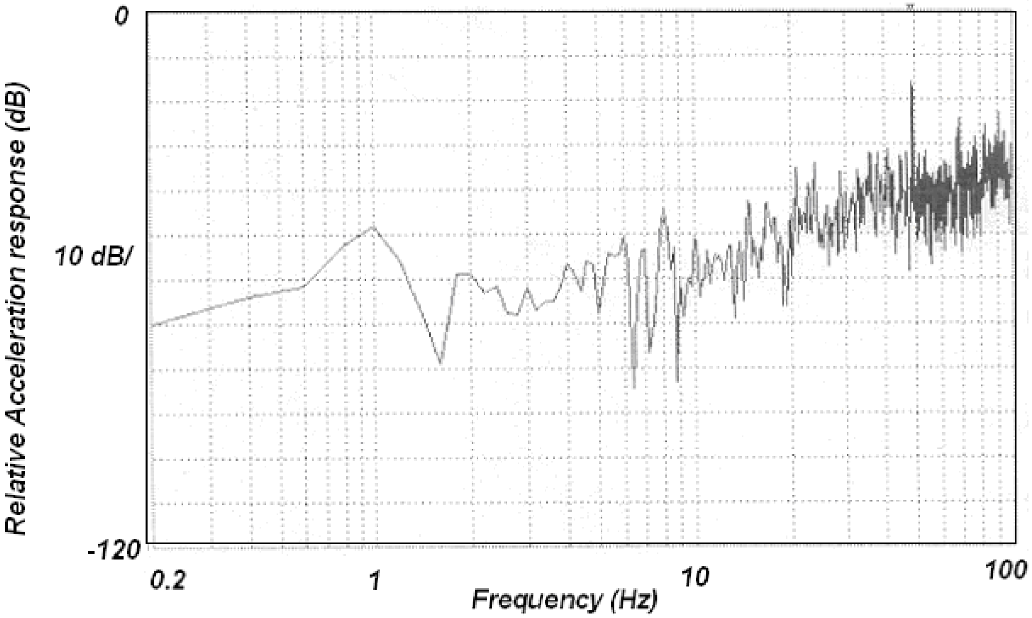

Figure 1. Vibration acceleration spectrum of a train passing at a distance of 4m with a speed of 80 km/h speed

It is evident from the spectrum that the frequency response of ground vibration with a characteristic peak near 50 Hz is caused by the resonance of the wheel mass against the stiffness of the track. The wheel passing frequency is observed at 1 Hz.

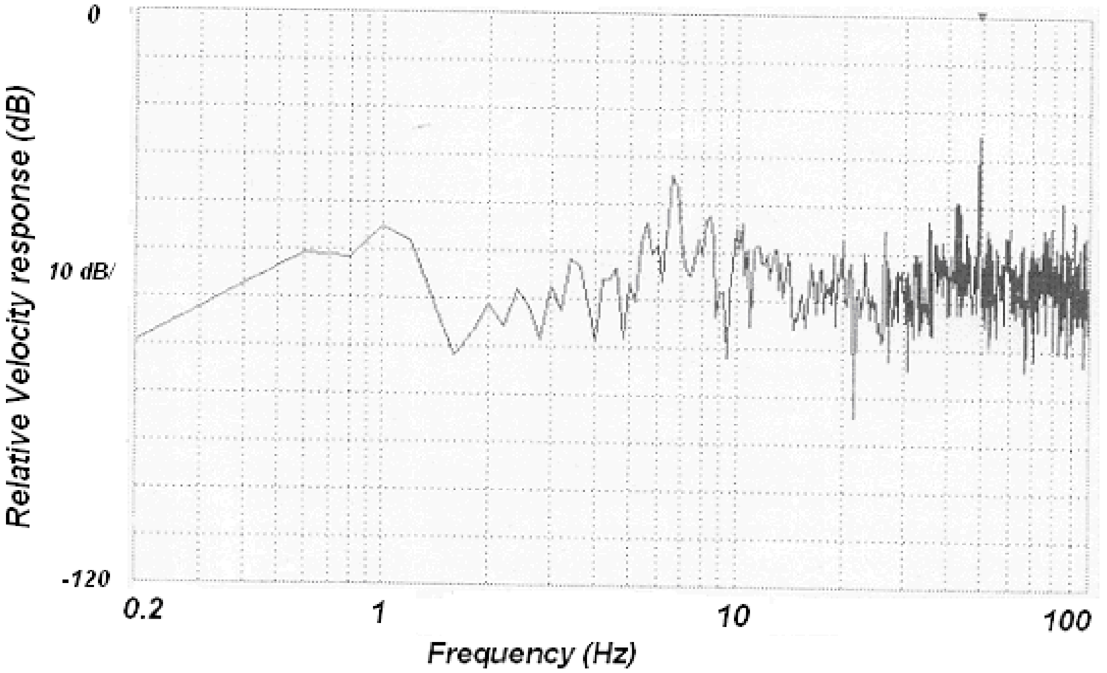

Figure 2. Vibration velocity spectrum of the passenger train passing at a distance of 4m with a speed of 80 km/h speed

The in-situ vibration levels were also monitored at Vidhan Sabha metro station with train approaching near the platform to assess the actual vibration generated by metro trains. The acceleration level at 5 m from centerline for a metro train running in tunnel at 50 km/h is shown in Fig. 3 & 4.

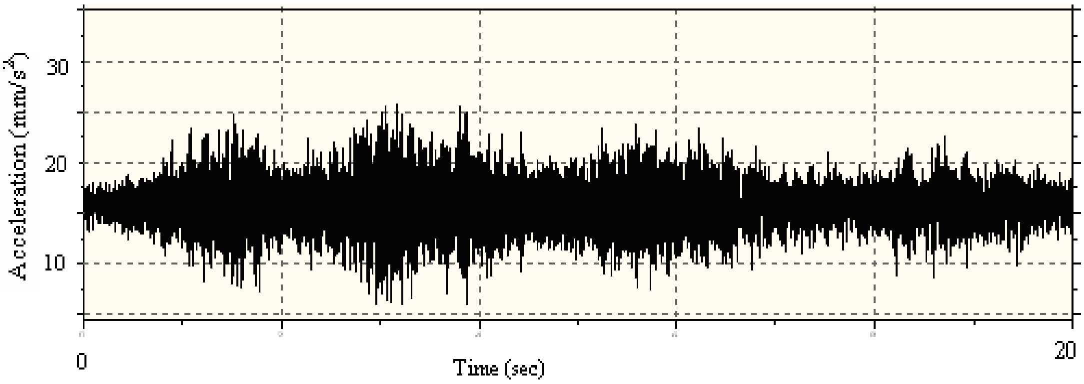

Figure 3. Approaching train acceleration spectrum (time-domain) at near line at 2 m from the edge of platform

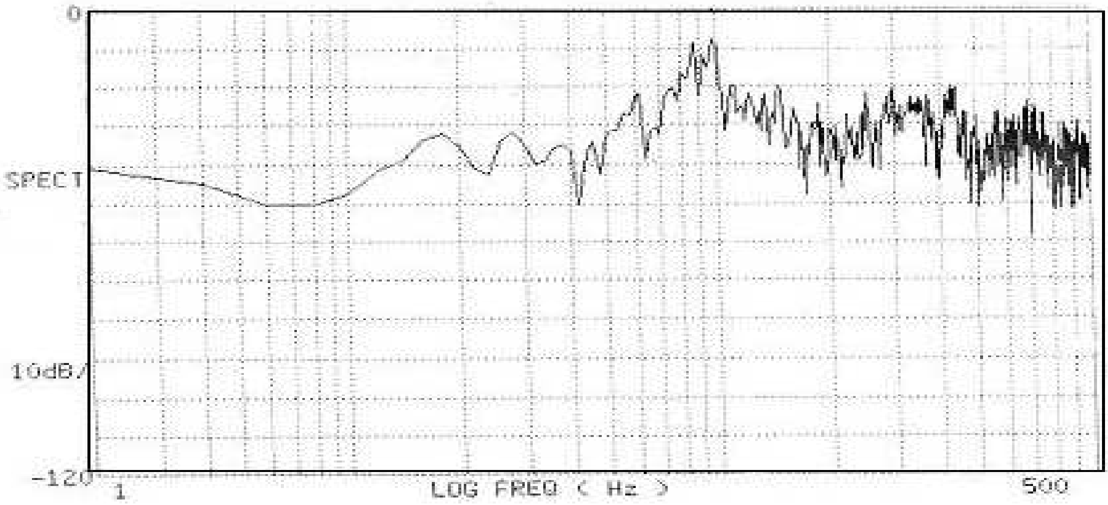

Figure 4. Approaching train acceleration spectrum (near line) at 2 m from the edge of platform

The rms acceleration generated by the metro train (near line) at 2 m from the edge of the platform is measured to be 20.2 mm/s^2 and an rms velocity of 47.8 µm/s. The frequency content of the measurements taken for train are quasi-discrete and are characterized by axle and bogie passing frequencies and related high-order harmonic frequencies as well as sleeper passing frequency and as the train speed increases, the peak moves towards the higher frequencies. The peak is observed to be at low frequency of 49 Hz. The low frequency ground vibration propagated by trains shall be perceived by listener as low frequency rumbling sounds, which may cause annoyance.

The in-situ traffic induced vibrations were measured on one side of the road at a distance of 4 m from the road. Fig. 6 shows the time domain measurements of acceleration measured. Vibration levels induced by transit buses were 1.5 to 2 times those induced by trucks of the same weight category. The lowest observed cutoff frequency was 2 Hz. Table 2 shows the summary of traffic induced ground vibrations measured at some sites including the road at the entrance to old historic monuments (Jantar Mantar and Red Fort) in Delhi city. The predominant frequencies and amplitude of the vibration depend on many factors including the condition of the road; vehicle weight, speed and suspension system; soil type and stratification; distance from the road; and type of building. The effects of these factors are interdependent and it is difficult to specify simple relationships between them [10].

Table 2. Measured vibration levels at various traffic locations and old historical mounuments in Delhi

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Location	**Floor**	**Average Acceleration (mm/s^2)**	**Average Velocity (mm/s)**
Rajendra Place	Ground	3.1	0.09
	First	2.1	0.03
	Second	1.1	0.05
	Third	0.7	0.04
Patel Nagar	Ground	2.7	0.05
	First	1.2	0.03
	Second	0.6	0.02
Kashmere Gate	Road side	3.5	0.06
Jantar Mantar (Old Historic monument)	Road side	4.3	0.02
Red Fort (Old Historic monument)	Road side	3.2	0.03
Tilak Nagar	Road side	2.8	0.04

It was observed that dominant frequencies of bus-induced vibrations were between 1-30 Hz, while those of truck induced vibration spread over the wider range. Variability in the absolute levels and frequency spectrum was observed for different vehicles which may be due to different mass of the vehicle and speed on different road surfaces (porous asphalt, bituminous, cemented etc.). Each measurement site exhibited a cutoff frequency as pointed out by Hunaidi et al. [19] below which acceleration levels were very small. The lowest observed cutoff frequency was 2 Hz. Fig. 5 shows the time domain analysis of acceleration due to road traffic at a particular location.

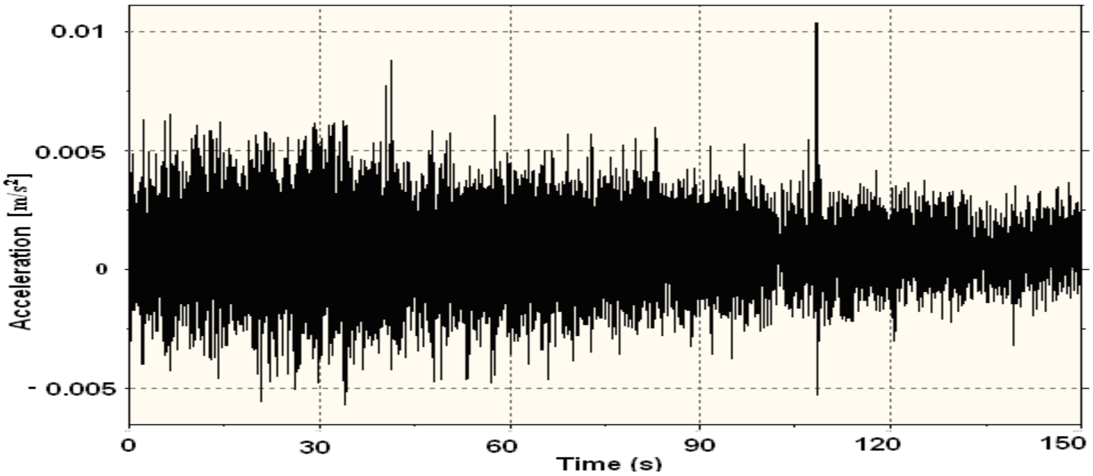

Figure 5. Acceleration in time domain for conventional city traffic

3. Impact of transportation induced vibrations

The transportation induced vibration exposure level cannot be represented in definite model due to different perception of receivers, building elements, soil types, suspension systems etc and thus a line of demarcation for building damage is varied in different international standards proposed so far. Thus, the subjective response may also vary due to different frequency composition and amplitude levels. The analysis of measurements conducted for train induced ground vibration reveals that the average ground vibration at 4 m distance from the center line was 130 mm/s^2 in acceleration mode and 336 ± 73 μm/s for passage of trains at a speed of 80 km/h. Thus, it can be inferred that there exists a safe margin of 15 dB for damage to occur, if a ppv of 3 mm/s is considered to be onset of damage. The passage of metro trains in an underground station at a speed of 50 km/h registers a vibration level of 20 mm/s^2 and an rms velocity of 47.8 μm/s at a distance of 5 m, which presents a larger safe margin for damage to occur. The acceleration levels smaller than 0.1 m/s^2 are safe for the buildings, but when reach a level 0.1-1.0 m/s^2, micro cracking of the building construction may occur. When the acceleration level exceeds 1 m/s^2, macro cracks are formed in the construction implying that they are being destroyed [20].

The noise level within a building element due to structural vibration is dependant on vertical floor vibration as proposed by Kurzweil. The floor vibration level L_a (room) can be estimated from

$$L_a\,(\text{room}) = L_a(\text{tunnel}) - C_g - C_{gb} - C_b \qquad [2]$$

Where L_a(tunnel) is octave band acceleration on the wall of a subway tunnel during a train pass by, C_g is vibration attenuation due to propagation throughout the ground, C_{gb} is coupling loss between ground and building and C_b is vibration attenuation due to propagation in the building. The sound pressure level in the room L_p (room) can be thus determined in terms of octave band centre frequency f as:

$$L_p\,(\text{room}) = L_a\,(\text{room}) - 20\log_{10} f + 37 \quad \text{dB} \qquad [3]$$

The estimated vertical floor vibration at 5 m distance away from the train shall cause an interior sound pressure level of 40 dB(A) (1/1 octave band 31.5, 63 & 125 Hz). The interior sound pressure level generated due to a metro train at a distance of 5 m shall cause an sound pressure level of 22 dB(A). Although this magnitude of structurally radiated interior noise level is insignificant compared to the ambient noise in a particular community, yet the low frequency noise shall cause more annoyance as compared to a broad band noise of same level. The total attenuation of vibration, A_T from a tunnel to a position, a distance x meter away, is given by Unger and Bender [21] approach:

$$A_T = A_S + A_d + A_i \qquad [4]$$

Where, $A_S = 10 \log_{10} (r_0 + x/ r_0)$, is spreading loss assuming the train to be a line source [5]

$A_d = 4.34\ \omega\eta x/c$, is the internal losses in the soil [6]

$A_i = 20 \log [\tfrac{1}{2} (1 + \rho_c c_c/\rho_a c_a)]$ accounts for change in the soil along the wave propagation path and r_0 is the tunnel radius. [7]

At 50 m away the attenuated peak particle velocity calculated shall be of the order 105 μm/s considering an isotropic clayey soil. The estimated vertical floor vibration at 40 m distance away shall cause an interior sound pressure level of 46 dB. While applying the A-weighted correction at the said frequency the SPL calculated for correlation to annoyance will be 23 dB. Thus, it can be inferred that low frequency rumbling noise radiated by train passage shall be of more concern to dwellings located in vicinity of track within a distance of 10 m.

The transportation induced vibrations may not produce physiological effects, but some times motion sickness may result due to low frequency dominance. The inhabitants perceive these vibrations as aural response, body vibration or structural damage to the building. Fig. 6 shows the annoyance versus vibration exposure level in VdB proposed by Federal transit Authority, US in 2005 [22]. The data indicate that residential vibration exceeding 75 VdB (0.14 mm/s) is unacceptable for a repetitive vibration source such as rapid transit trains that pass every 5 to 15 minutes, while 65 VdB (0.04 mm/s) is considered as threshold of perception.

It can be concluded from the figure that for vibration level more than 70 VdB (0.08 mm/s), more than 20 % people feel annoyed, while for levels more than 75 VdB, more than 50 % of the people feel annoyed. Thus, considering the levels generated by passage of train registering a vibration level of 90 VdB (336 μm/s) and overall attenuation of 20 dB due to geometrical and material damping, shall cause around 40 % annoyed population in immediate vicinity of the track. The traffic induced vibration levels of order of 74 VdB (0.05 mm/s) reaching the receiver, shall be on the border line for threshold of perception.

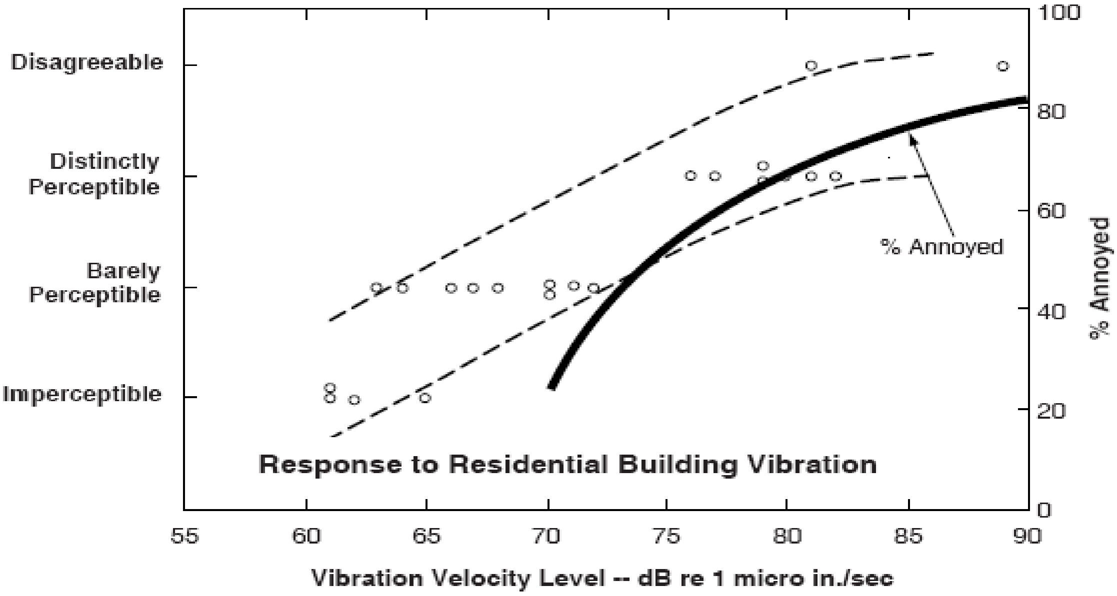

Figure 6. Occupant response to transit train induced vibrations (FTA, 2005)

The exposure-effect curves of Norwegian Standard NS 8176.E:2005 Standard [23] state that 10% of building occupants will be highly annoyed if the peak particle velocity measured is 0.5 mm/s due to ground vibrations induced by heavy commercial vehicle. The percentage highly annoyed increases to 20% if the peak particle velocity measured is 1.7 mm/s. Thus, for an exposure level of an order of 0.05-0.1 mm/s, there seems to be a safe margin in community response to ground vibrations.

4. Conclusions

A limited study of vibration due to transportation means is presented. The study infers there is a wide margin in between the occurrence of measurable vibration and the onset of structural damage in building unless the vibrations are of higher magnitude and of a sustained nature. The ground vibrations corresponding to normal traffic conditions are not strong enough to cause damage to structures, but they might be perceptible by occupants and might impede normal operations of sensitive equipment. Some anti-vibration measures such as adding the damping device, isolating the structures from ground vibrations or use of trenches (either open or backfilled with light-weight water proof filler) and solid barriers (e.g. concrete filled trenches) may prove to be an effective measure to combat the transportation induced vibration. However, rigorous measurements on different rail and traffic sources operating at different speeds in different soil conditions is essential for establishing a definite model to quantify the vibration exposure level due to transportation. Extensive experimental investigations for establishing a model for evaluation of the vibration exposure level, characterizing the propagation characteristics and its attenuation with distance is thus very vital futuristic need to ascertain the impact of ground borne vibrations induced due to mass transit systems and ever-increasing vehicular traffic.

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