

Mitigation of Highway Traffic-Induced Vibration

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ABSTRACT

Occasionally, transportation agencies receive complaints from residents living near roads about annoying or even structurally-damaging traffic-induced vibration. The resolution of these complaints can be very challenging because many transportation agencies do not have guidelines for the assessment of the potential impact of traffic-induced vibration. Many agencies may also lack experience with dealing with vibration complaints, and with measures to mitigate the impact of traffic-induced vibration.

The paper describes sources of traffic-induced vibration, identifies possible causes that may result in vibration concerns, and outlines procedures for estimating vibration levels caused by highway traffic. In addition, the paper provides guidelines and recommended criteria for the assessment of vibration impacts on residential areas, and provides recommendations for the mitigation of traffic-induced vibration. Both types of traffic induced vibration – ground-borne vibration and air-borne vibration – are addressed.

The assessment of the impact of vibration can be accomplished by estimating the site-specific vibration levels and comparing them with assessment criteria and guidelines. The site specific factors influencing vibration levels include the characteristics of the highway traffic flow, unevenness of pavement surface, transmission path between the source and the receiver, and building parameters. In extreme circumstances, traffic-induced ground-borne vibration may be perceptible to residents living near roads. However, it is very unlikely to result in damage to residential buildings. Air-borne vibration may increase sound levels inside residences due to the resonance of light building components. The vibration of these components can also contribute to the feeling of vibration inside a room. The first consideration for removing the potential for ground-borne vibration is the maintenance of smooth pavement surfaces. The considerations for reducing the potential for air-borne vibration include improving windows, making the interior of the rooms more sound absorbing, and eliminating room components that can be induced to resonate by low-frequency noise emitted by trucks and buses.

INTRODUCTION

It is usual for large transportation agencies to receive complaints from residents living near highways about annoying highway noise. Complaints about vibration caused by highway traffic are less frequent, but they do occur. Typically, vibration complaints are also accompanied by complaints about excessive highway noise. Many transportation agencies do not have applicable guidelines for the assessment and resolution of vibration complaints. The objective of this paper is to provide a better understanding of highway traffic induced vibration and to outline procedures for its assessment. Specific topics discussed in the paper include:

- Causes and types of highway traffic induced vibration.
- Variables influencing vibration levels near highways.
- Procedures for estimating vibration levels caused by highway traffic.
- Recommended criteria and guidelines for vibration impact assessment.
- Mitigating measures for vibration induced by highway traffic.

DESCRIPTION OF VIBRATION

Vibration is an oscillatory rapidly fluctuating motion of a medium. The oscillatory motion causes particles to move in a retrograde ellipse as illustrated in Figure 1. Because the motion is oscillatory, there is no net movement of the vibratory element. The oscillatory motion is propagated forward in a wave motion. The difference between the oscillatory particle motion and wave propagation is analogous to the difference between the bobbing of a cork on the surface of a body of water and spreading out of ripples on the water surface -- the cork oscillates but does not move forward.

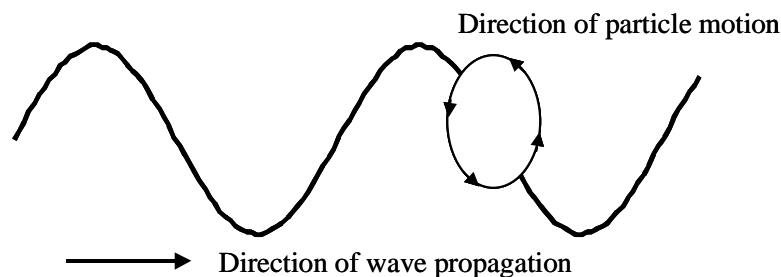


Figure 1. Vibratory motion

Vibration of the air that can be heard by people is called sound. Sound that annoys is called noise. Vibration of materials other than air is called simply vibration. We speak about vibration of a string, floor or, ground.

A complete description of the vibratory motion at a point requires six variables corresponding to three directional components and three rotational components. Any of these six variables can be characterized by amplitude (maximum displacement), or by velocity (the instantaneous speed of the movement), or by acceleration (the rate at which the speed changes). For practical purposes for assessing traffic induced vibration, it is sufficient to use only one predominant component of the vibratory motion. The selected component is the directional vertical component which is typically characterized or measured in terms of the vibration velocity [1]. The vibration velocity is defined as the peak particle velocity (PPV) of

vibratory motion (corresponding to the maximum instantaneous positive or negative vibration velocity), or as a root mean square of the peak velocity. The formula for converting peak velocity (*Peak*) to rms velocity (*rms*) for a sine wave is given in Equation 1.

$$rms = \frac{Peak}{\sqrt{2}} \quad \text{Equation 1}$$

Figure 2 shows a vibration signal of a short transient vibration of ground caused by a truck axle. The mean of all vibration movements is zero.

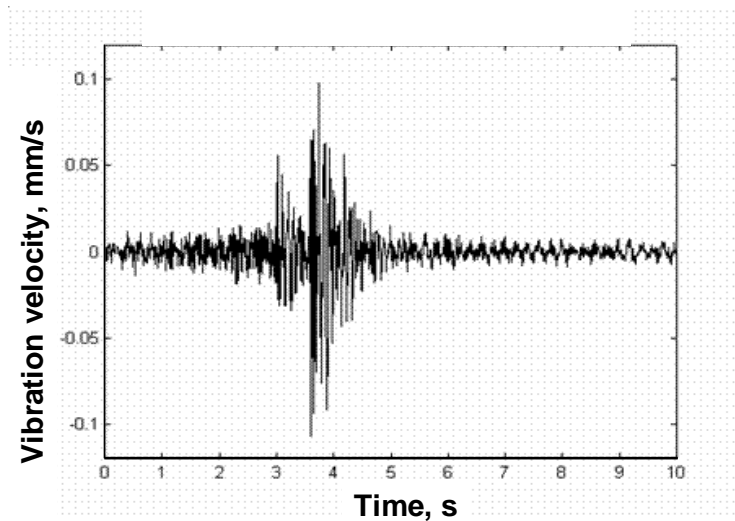


Figure 2. Vibration signal displayed on an oscilloscope. Source: Reference 2.

TYPES OF TRAFFIC INDUCED VIBRATION

There are two ways in which highway traffic can induce vibration in nearby buildings:

- *Ground-borne vibration* caused by the dynamic impact forces of tires on the pavement surface that can propagate and excite footings and foundation walls below ground. Vibration of footings and foundation walls can induce vibration in other building components below or above ground.
- *Air-borne vibration* caused by low frequency sound that can excite building components above ground.

These two types of vibrations can be caused by the passage of the same vehicle at the same time.

Ground-Borne Vibration

Ground-borne vibration is caused by the interaction between the dynamic forces produced by tires of highway vehicles and pavement surface irregularities. Pavement surface irregularities can be classified as random pavement surface irregularities or as specific pavement surface irregularities.

Random pavement surface irregularities exist on all pavements and are typically characterized by measures of pavement smoothness or roughness such as the International Roughness Index (IRI). Typically, random surface irregularities can result in randomly occurring dynamic forces that are up to 15

percent higher than the corresponding static forces [3]. The impact of these dynamic forces on pavements results in randomly occurring ground-borne vibration. Although random ground-borne vibration is always present (the pavement is never completely smooth and highway vehicles are never completely dynamically inert), it is too low to be perceived even by observers very close to the source.

Specific pavement surface irregularities, such as potholes and stepped transverse cracks, can significantly increase the force of the tire striking the pavement. Compared to the static force, the dynamic force may be up to 50 to 80 percent higher. The higher dynamic forces result in proportionately higher ground-borne vibration. Consequently, main generators of highway traffic induced vibration are specific surface irregularities.

There are three basic types of dynamic tire forces acting on the pavement surface simultaneously (Figure 3).

1. *Impact forces of the individual parts of the tire tread.* The impact frequency of these forces on the pavement, at highway speeds, is typically in the range of 800 to 1500 Hz, depending on the pavement macrotexture and on the tire tread pattern. Although the forces associated with the individual parts of the tire tread are significant producers of pavement-tire noise, their contribution to the ground-borne vibration is negligible. Reference 4 provides a good review of the influence of pavement surface on highway traffic noise.
2. *Impact forces linked to the unsuspended mass of the vehicle.* The unsuspended vehicle mass is the mass below the vehicle suspension system, mainly axles, wheels, and tires. At highway speeds, a specific part of the tire comes into contact with the pavement surface about 10 to 15 times per second. This frequency is related to the frequency of the tire bounce (also called axle hop).
3. *Impact forces linked to the fundamental frequency of trucks.* At highway speeds, a typical 5-axle tractor semi-trailer has the fundamental frequency of the suspended mass of about 1 or 2 Hz. Thus, the suspended mass (the part of the truck supported by the suspension system) heaves up and down about 1 or 2 times per second as the truck moves at highway speeds. When the truck heaves down, its static weight on the pavement increases due to the dynamic motion component.

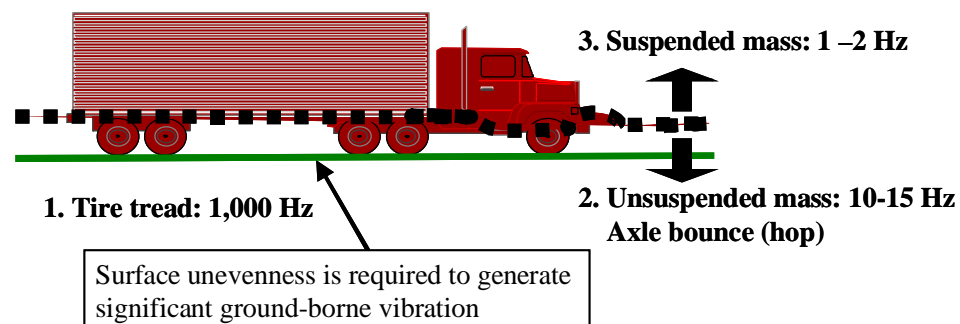


Figure 3. Source of vibration caused by a truck

The three types of tire impact forces interact and produce ground-borne vibration with the dominant frequency, at highway speeds, between 10 and 15 Hz. Highway traffic induced ground vibration is a forced, non-resonant, vibration of the pavement/subgrade system. The non-resonant property of the vibration means that the pavement structure/subgrade system is inert and does not amplify the forced vibration [5].

Air-Borne Vibration

Air-borne vibration is caused by low frequency sound, produced by engines and exhaust systems of large diesel trucks, which can excite building components above ground. The fundamental frequency of truck exhaust systems (engine combustion and firing) is typically 50 to 200 Hz, and this frequency may correspond to the fundamental frequency of light building components. Consequently, the variation in sound pressure (or vibration of the air) that impinges on the building components can result in excitation or vibration of these components. The key to the generation of air-borne vibration is resonance – repeated excitation of building components and other elements at their fundamental frequency. Light flexible elements of a structure, such as window panes and door panels, may start to vibrate independently of other elements when resonance is achieved. The result may be, for example, an audible rattle of loose windows [6].

There is also a possibility of acoustical coupling of the light building elements with the acoustical properties of the room. In this scenario, sound pressure variation that is transmitted through the window panes, exterior walls, or through an open window is coupled with sound pressure variation produced by excitation of light building elements and with sound pressure levels reflected from the surfaces of the room. This may result in increased sound levels inside the room and in vibration of the light room elements such as rattling of stacked dishes or cups on a shelf.

Interaction Between Noise and Vibration

There is a correlation between the way people perceive highway noise and highway traffic induced vibration [7]. With the increase of sound level, the number of people who complain about high noise level increases and so does the number of people who complain about vibration. Sound and vibration caused by the same source also interact. For example, sound may result in vibration of a window pane and the pane may rattle. Or, in an extreme case, ground-borne vibration can vibrate room surfaces, such as a floor, and produce ground-borne noise in the form of rumbling sound. This is known to occur near railway lines [8, 9].

The noise and vibration impact on a building occupant results from a combined effect of sound (penetrating the room, reflected from the room surfaces, and emitted by vibrating room components such as a window pane) and perceived vibration of building elements.

FACTORS INFLUENCING VIBRATION

The main factors influencing traffic induced vibration are shown in Figure 4. These factors include the source of vibration, transmission path, and the receiver.

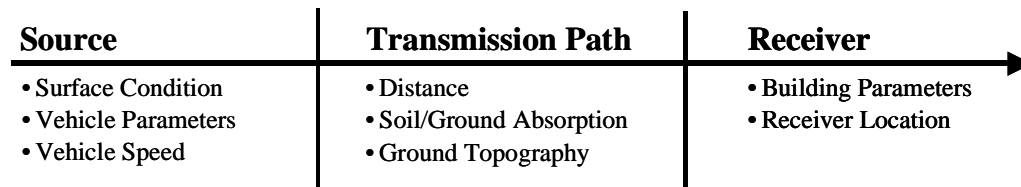


Figure 4. Main variables influencing traffic induced vibration

Source of Vibration

The condition of the pavement surface is the decisive contributor to ground-borne vibration. It is also the most significant factor that can be controlled by highway agencies. Discrete pavement discontinuities, such as stepped transverse cracks exceeding about 4 mm, appear to be significant enough to overshadow the effect of random surface roughness and result in specific sources of vibration. Potholes or bumps, typically more than 25 mm in depth or height and about 150 mm long, are necessary to overshadow the effect of random pavement roughness. The different criteria for transverse cracks, compared to potholes, stem from the observation that transverse cracks are typically perpendicular to the direction of travel and affect all wheels of the axle simultaneously. Pavement discontinuities closest to the observer are of primary importance because ground-borne vibration decreases rapidly with distance from the source.

In a recent case, a vibration complaint, by a resident living in a two-story residential dwelling about ten meters from the edge of pavement of an urban freeway, was probably triggered by a very severe stepped pavement transverse crack located close to the residence. Stepped transverse cracks can also cause loud bangs when empty dump trucks bounce on them, contributing further to highway traffic noise and the perception of vibration.

There are several vehicle characteristics that can influence vibration. Heavier vehicles produce higher ground-borne vibration (because of the larger mass acting on the pavement) and typically higher sound levels. Trucks equipped with steel (leaf-spring) suspension can produce higher dynamic loads and vibrations compared to trucks equipped with air suspension. Stiff, over inflated tires do not exhibit “enveloping effect” and may bounce more readily over surface irregularities, resulting in higher dynamic forces. Jake brakes, also known as compression release engine breaking systems, can significantly increase exhaust and engine noise during breaking operations.

An increase in the number of heavy trucks results in more vibration peaks, not necessarily higher vibration peaks. This is because of the rapid drop-off of vibration peaks with distance from the source, and the short duration of the vibration peak (Figure 2). However, the increase in the volume of heavy trucks increases the probability of the occurrence of particularly heavy trucks and trucks with malfunctioning suspension and exhaust systems. Higher vehicle speed increases both ground-borne vibration and sound levels.

Transmission Path

The propagation of traffic-induced vibration from the source depends on the distance from the receiver, frequency of vibration, topography between the source and the receiver, and on the soil and other geotechnical characteristics of the ground. Vibration propagates through the ground in the form of body waves (compression and shear waves), and in the form of surface or Rayleigh waves (Figure 5).

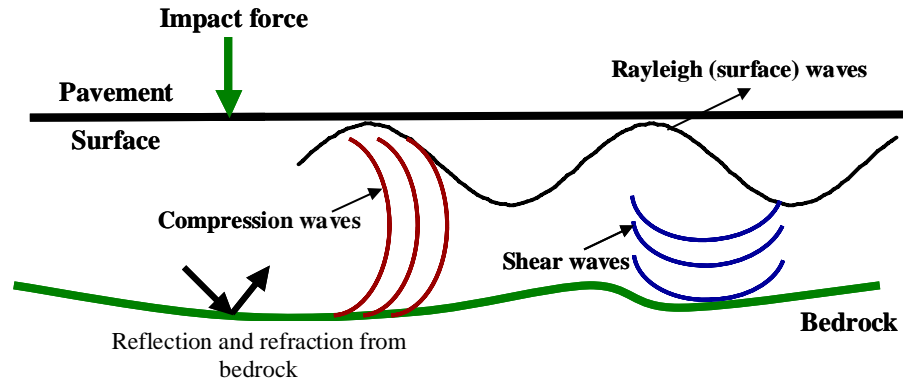


Figure 5. Propagation of ground-borne vibration

The Rayleigh waves are the most important form for the propagation of traffic induced vibration because at the ground level the amplitude of the Rayleigh waves decreases (due to geometric spreading) as the inverse of the square root of the distance from the source, while the amplitude of body waves decrease as the inverse of the square of the distance from the source [10].

Specific surface discontinuities represent a point source from which ground-borne vibration spreads and is attenuated, theoretically, as the inverse square root of distance. However, soil absorption plays decisive role in vibration attenuation with distance. Recent data from Sweden [2] and data from the United Kingdom [10,11] indicate that dry sand and gravel soils have the highest capability to absorb vibration, while soft clay or peat have the lowest.

The significant influence of the soil type on the propagation of ground vibration is illustrated in Figure 6. Absorptive effects of soils in attenuating ground vibration are also highly frequency dependent. The higher frequency components of the ground vibration attenuate much more rapidly with distance than the low frequency components [1]. Not surprisingly, the same influence of the frequency applies to the propagation of sound.

Receiver

Ground-borne vibration transmitted through the ground to foundation footings or foundation walls can spread to other parts of the building. The amount of vibration experienced by an observer depends on building parameters and on the location of the observer in the building. Typically, the vibration of floors or walls above ground is larger than vibration of basement walls. For example, the results of measurements reported by Rudder [1] and Watts [11] indicate that vibration of floors can be significantly higher than the corresponding vertical vibration at foundations. Measurements carried out on one-and-two-story buildings indicate that vibrations increase with height above ground. The increase of vibrations with building height may not apply above a certain building height above the ground.

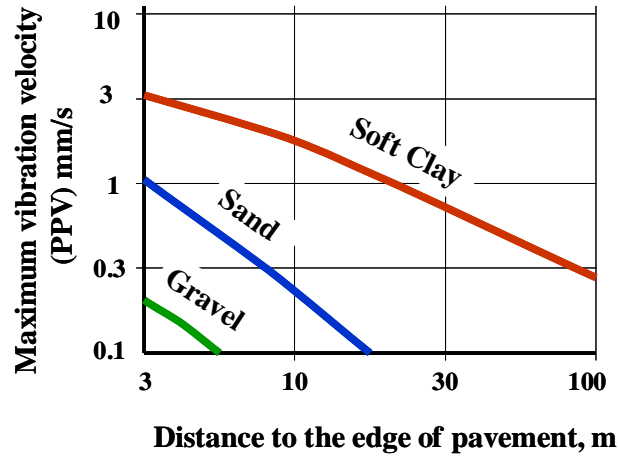


Figure 6. Effect of soil type on the propagation of vibration

ESTIMATION OF GROUND-BORNE VIBRATION

Field measurements and/or analytical estimation of ground-borne vibration are challenging tasks. The measurements are highly dependent on the measurement location and the manner in which the measurement sensors are mounted. Analytical estimation of ground-borne vibration depends on many interacting variables characterized by complex parameters. To simplify the analytical estimation of vibration levels, Watts [11] developed the following approximate formula for determination whether the maximum peak particle velocity (PPV) at a foundation level, caused by highway traffic, is significantly in excess of the threshold of perception:

$$PPV = 0.0028 a (V/48)^t p (r/6)^x \quad \text{Equation 2}$$

Where:

- PPV = Peak Particle Velocity in the vertical direction, mm/s.
- a = Maximum height or depth of the surface defect in mm.
- v = Maximum expected speed of trucks in km/h.
- t = Scaling factor to account for soil type.
- p = Coefficient to account for the occurrence of the defect in one or both wheel paths (p = 1 if the defect is in both wheel paths; p = 0.75 if the defect is only in one wheel path.)
- r = Distance of the receiver from the surface defect in m.
- x = Power factor to account for vibration attenuation in different soils.

To facilitate rapid assessment of highway induced ground vibration, the California Department of Transportation developed a graph showing a relationship between the expected maximum highway traffic vibrations with distance [12]. The distance is measured from the centreline of the nearest freeway lane (Figure 7). The graph assumes that the highest highway traffic generated vibration, measured on a freeway shoulder (5 m from the centre of the nearest lane), cannot exceed 2 mm/s. Also shown in Figure 7 are recommended vibration impact assessment criteria that are discussed in the next section.

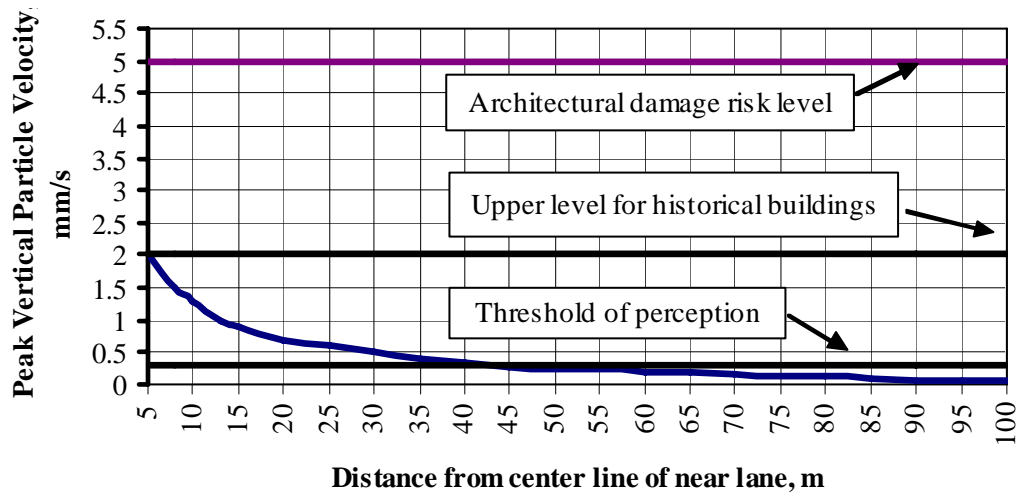


Figure 7. Maximum highway truck traffic vibration levels versus distance

ASSESSMENT OF GROUND-BORNE VIBRATION

The process of assessing a potential ground-borne vibration problem consists of establishing vibration levels at the receiver and comparing them with acceptance criteria.

Assessment Guidelines and Criteria

Researchers at the UK Transport and Road Research Laboratory (TRRL) carried out a considerable amount of work on highway traffic induced ground-borne vibration and developed guidelines for assessing vibration caused by highway traffic. Whiffin and Leonard [3] proposed the guidelines presented in Table 1 to assess effects of vibration on people and buildings.

With the construction of new rail rapid transit systems in North America during the past 20 years, considerable experience has been gained as to how communities will react to various levels of building vibration caused by rail transit systems. Criteria related to ground-borne vibration recommended by the US Federal Transit Administration and by the US Federal Railroad Administration are presented in Table 2 [8, 9]. The original criteria in References 8 and 9 are expressed as decibel values referenced to the reference velocity of 1×10^{-6} inches per second. For ease of comparison with criteria given in Table 1, we have converted the velocity values given in decibels (and referenced to inches per second) to the absolute velocity values in terms of millimetres per second, and summarized the results in Table 2.

The guidelines used by the California Department of Transportation [12] to evaluate the severity of vibration problems caused by highway traffic, given in Figure 7, are similar to those presented in Tables 1 and 2, considering that the vibration criteria given in Table 1 are in the form of PPV and the vibration criteria in Table 2 are in the form of rms. (The relationship between PPV and rms for a sign wave is given by Equation 1.)

Table 1. Effects of Vibration on People and Buildings according to TRRL

PPV ^a (mm/s)	Human Reaction	Effect on Buildings ^c
0 – 0.15	Imperceptible	Unlikely to cause damage of any type
0.15 – 0.3 ^b	Threshold of perception	Unlikely to cause damage of any type
2.0	Vibrations perceptible	Recommended upper level to which ruins and ancient monuments should be subjected
2.5	Continuous exposure to vibrations begins to annoy ^d	Virtually no risk of “architectural” damage to normal buildings
5	Vibrations annoying to people in buildings	Threshold for risk of “architectural” damage in houses with plastered walls and ceilings
10 - 15	Continuous vibrations unpleasant and unacceptable	Would cause “architectural” and possibly minor structural damage.

^a Peak Particle Velocity in the vertical direction. For human reaction, the value applies at the point at which the person is situated. For buildings, the value refers to the ground motion (but without an allowance for the amplifying effect of structural components). It is assumed that the frequency of vibration is in the range of 5 to 20 Hz.

^b This level applies to a continuous sinusoidal vibration. However, truck induced vibration is of shorter duration (about 2 to 3 seconds) and thus higher levels appear to be applicable.

^c The criteria for buildings recognize that the building damage will result from a fatigue failure over a long period of time (not from a one-time event) .

^d Vibration levels causing annoyance may be lower for occurrences during night time and for occurrences that are very frequent [1].

Table 2. Ground-Borne Vibration Impact Criteria according to US DOT

Land Use Category	Ground-Borne Vibration Impact Levels (mm/s, rms)	
	Frequent ^a Events	Infrequent Events
Residences and buildings where people normally sleep	0.10	0.25
Institutional land uses with primarily daytime use	0.14	0.36

Source: References 8 and 9.

^a Frequent Events are defined as more than 70 vibration events per day where an event is considered to be a passing train of a rapid transit system.

Discussion

Based on experience with the nature of complaints received from residents living near highways and extensive literature review, highway traffic induced vibration may cause minor superficial or architectural damage to houses only in very extreme circumstances [14]. An extreme circumstance is a heavy truck travelling at a speed of more than 60 km/h over a pavement surface discontinuity caused by a wooden

plank 25 mm high and 600 mm wide spanning a traffic lane and the location of an exterior wall less than 10 m from the pavement edge. Such extreme circumstances seldom exist in practice. For example, Watt evaluated the effect of traffic vibrations on eight old (heritage) buildings, mostly residential dwellings [6]. All buildings were situated within a few meters of roadways carrying trucks. Some building walls were only 2.9 m from a severe pavement surface irregularity causing vibration. Even for these extreme situations, the peak vertical velocity at foundations did not exceed 1.0 mm/s. Whereas these vibration levels were classified as perceptible, they were well below levels known to cause even minor damage. It is possible that traffic induced ground-borne vibration can be perceptible inside a house situated very close to a roadway with pavement exhibiting significant surface irregularities. However, at the same time, the major cause of highway nuisance experienced by residents in this case would be related to air-borne vibration or to highway noise.

It is common for a tractor trailer to produce a peak sound level of 90 dBA at the distance of 15 metres. Considering point source attenuation, the sound level 50 metres from the edge of pavement can still be quite high and disturbing (about 80 dBA). Heavy trucks, particularly with Jake brakes engaged, can produce predominant low frequency noise in the range of 50 to 200 Hz. The attenuation of low frequency sound with distance is lower than that for higher frequency sound waves. The low frequency sound may also cause resonance of exterior and interior building elements (such as windows or shelves), contributing to the feeling of vibration experienced by residents. Air-borne vibration can be controlled by increasing the sound transmission loss of exterior walls, doors and windows, tightening of loose elements of a building or a room, and making the interior of rooms more sound absorbing.

The first consideration for removing the suspicion that traffic-induced ground-borne vibration can occur is the maintenance of smooth pavement surfaces. The maintenance of a smooth surface is important to minimize sound levels and the belief that vibrations are occurring. For example, an unloaded dump truck can produce a startling bang when its body bounces over a pothole.

CONCLUSIONS

1. The primarily cause of highway traffic-induced ground borne-vibration are dynamic forces of truck tires generated by specific pavement surface discontinuities (e.g., stepped transverse cracks, and potholes).
2. Highway traffic induced ground vibration is a forced, non-resonant, vibration of the pavement/subgrade system with the dominant frequency between 10 and 15 Hz. The pavement structure/subgrade system is inert and does not amplify vibration.
3. Only in very extreme circumstances, highway traffic induced ground-borne vibrations may cause minor superficial or architectural damage (such as cracking of plaster or cracking of drywall joints).
4. Highway traffic induced ground-borne vibration can be perceptible in very extreme circumstances. However, typically, the feeling of vibration reported by residents living near highways is due to low-frequency sound levels produced by trucks that can cause resonance of light exterior or interior building and room elements.
5. Ground-borne vibration induced by highway traffic can be effectively controlled by the maintenance of smooth roadway surfaces.

6. The solution for air-borne vibration is increasing the sound transmission loss of exterior walls, doors and windows, tightening of loose elements of a building or a room, and making the interior of rooms more sound absorbing.

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