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Traffic Vibrations in Buildings

by Osama Hunaidi

This Update describes the nature and causes of traffic-induced vibrations in buildings, and discusses possible remedial and preventive measures. The focus is on houses.

Vibration is a frequent problem in buildings. Common internal sources are machinery, HVAC systems, elevators and the activities of occupants. External sources include earthquakes, wind, blasting and construction operations, and road and rail traffic. This Update addresses vibrations caused by road traffic.

Vibrations induced by road traffic are a common concern in cities in Canada and worldwide. House owners may complain about annoyance and building damage. There may be concern about the possibility of adverse long-term effects of vibrations on historic buildings, especially those in a weak condition. Vibrations may also interfere with sensitive processes, such as those in hospital operating theatres, scientific research laboratories and high-tech industries.

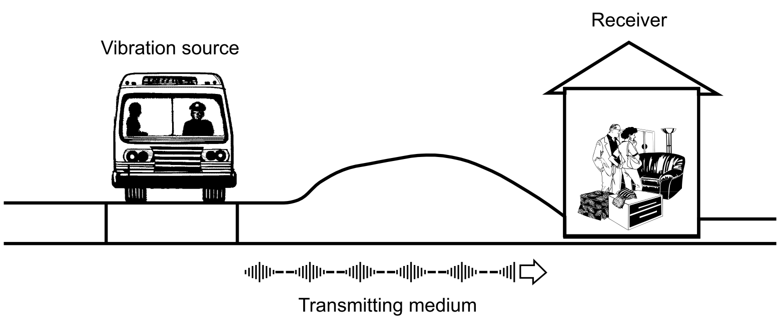

Figure 1. Traffic vibrations can be characterized by a source-path-receiver scenario.

How Traffic Generates Vibration

Like most vibration problems, traffic vibrations can be characterized by a source-path-receiver scenario (Figure 1). Vehicle contact with irregularities in the road surface (e.g., potholes, cracks and uneven manhole covers) induces dynamic loads on the pavement (Figure 2). These loads generate stress

Figure 2. Vibrations are generated when a bus or truck strikes an irregularity in the road surface.

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waves, which propagate in the soil, eventually reaching the foundations of adjacent buildings and causing them to vibrate. Traffic vibrations are mainly caused by heavy vehicles such as buses and trucks. Passenger cars and light trucks rarely induce vibrations that are perceptible in buildings.

*Table 1. Comparison of vibration levels (mm/sec², rms) induced by a bus and a truck, to demonstrate the effect of different suspension systems at different speeds**

Location	25 km/h		50 km/h	
	Bus	Truck	Bus	Truck
Ground in front of house	20.5	19.9	64.5	33.2
External foundation wall	11.2	10.1	30.9	15.7
Mid-point of floor in 1st storey	20.3	20.8	62.9	30.1
Mid-point of floor in 2nd storey	35.0	37.3	96.2	46.7

* Bus had air-bag suspension system; truck had multi-leaf steel spring suspension system.

When a bus or a truck strikes an irregularity in the road surface, it generates an impact load and an oscillating load due to the subsequent "axle hop" of the vehicle. The impact load generates ground vibrations that are predominant at the natural vibration frequencies of the soil whereas the axle hop generates vibrations at the hop frequency (a characteristic of the vehicle's suspension system). If the natural frequencies of the soil coincide with any of the natural frequencies of the building structure or its components, resonance occurs and vibrations will be amplified.

In contrast to irregularities such as manhole covers or potholes, normal road surface roughness induces continuous dynamic loads on the road. If the road surface roughness includes a harmonic component that, at the posted speed, leads to a forcing frequency that coincides with any of the natural frequencies of the vehicle and/or those of the soil, substantial vibration may be induced. This effect is familiar to car drivers travelling over dirt or gravel roads with ripples (termed "the washboard effect"). At a certain speed, the vehicle shudders excessively but the vibration subsides at higher or lower speeds.

Factors Influencing Vibration Level and Frequency

Road traffic tends to produce vibrations with frequencies predominantly in the range from 5 to 25 Hz (oscillations per second). The amplitude of the vibrations ranges between 0.005 and 2 m/s^2 (0.0005 and 0.2 g) measured as acceleration, or 0.05 and 25 mm/s measured as velocity. 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 effect of vehicle speed, for instance, depends on the roughness of the road. Generally, the rougher the road, the more speed affects the vibration amplitude. The effect of the suspension system type also depends on vehicle speed and road roughness. For low speed and smooth road conditions, the effect of the type of suspension system is not significant. But for high speeds and rough roads, the type of suspension system becomes important (Figure 3). This interdependence can be seen in Table 1, which presents vibration levels recorded for a transit bus and a truck of the same weight category, travelling on a rough road. Vibration levels induced by the two vehicles were similar at 25 km/h. At 50 km/h, however, vibration levels induced by the bus were about twice those induced by the truck.[1]

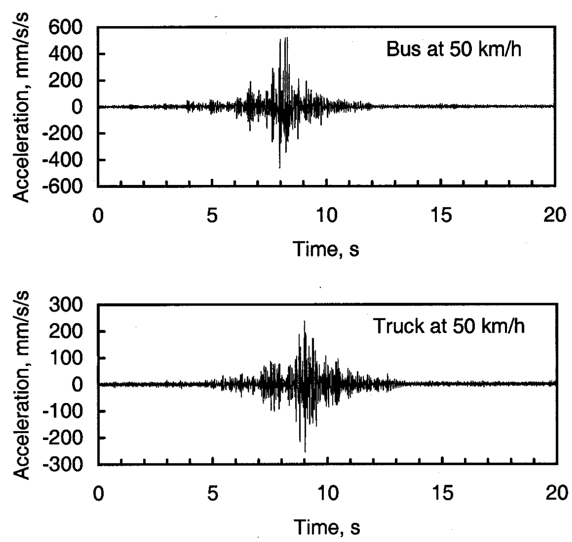

Figure 3. Comparison between vibration levels induced by a transit bus and a truck. Vibration levels are significantly different because of differences in suspension systems.

Vibration amplitudes and the predominant frequencies are influenced significantly by the soil type and stratification. The lower the stiffness and damping of the soil, the higher the vibration. For impact loads, ground vibrations are highest at the natural frequencies of the site. At these frequencies, the soil, like any structural system, offers the least resistance and hence the greatest response to loads. For soils, the natural frequencies depend on stiffness and stratification. Typically, traffic vibrations are worst in areas underlain by a soft clay soil layer that is between 7 and 15 m deep. In these areas, the natural frequencies of the soil can coincide with those of houses and their floors, leading to resonance or amplified vibration.

In Canada and other northern countries where the topsoil is normally frozen in winter, vibration levels in winter can be less than half the levels occurring in other seasons. Generally there are fewer complaints about vibrations in winter. The number of complaints is usually highest during the spring thaw period. It is commonly believed that the high ground water table at this time increases vibration levels; evidence based on experiments, however, shows that vibration levels in the spring are only slightly higher than those in the fall and summer. The higher number of complaints in the spring may be due to the lower vibration levels during winter. The 'quiet' winter period may cause a loss of familiarity with vibration and consequently a decrease in tolerance as vibration levels increase again in spring.

Vibration levels decrease with distance from the road as a result of "geometrical spreading" of the vibration energy and its dissipation by soil viscosity and/or friction. By way of example, geometrical spreading is the effect by which ripples induced by throwing a stone into a pond become flatter as they spread out. For homogeneous soil sites, vibration propagation patterns are simple, and general simple relationships can be found between vibration levels and distance. In general, however, soils are rarely homogeneous and are usually stratified. Propagation patterns are, therefore, very complex, and attenuation relationships are site-specific.

Airborne Vibration

The noise of passing buses and trucks can also induce vibrations, especially if buildings are close to the road. These airborne vibrations occur at higher frequencies than soil-borne vibrations and mostly cause rattling of windows and loose objects in front-facing rooms of affected buildings.

Measurement and Analysis of Vibrations

For proper evaluation of the effect of building vibrations induced by road traffic, measured vibrations must be undistorted and data processing and analysis must follow established procedures.[2] Instrumentation for the measurement of vibration signals, which usually includes vibration sensors, signal conditioners and recording equipment, should have sufficient resolution and sensitivity. Measurements should be made at locations where the vibration levels reflect the purpose of the evaluation. To evaluate the effect of vibrations with respect to human annoyance, measurements should be taken at locations where the vibration level is greatest, normally at the midpoints of floors. On wood floors, the measurement points should be located near joists to avoid local resonance of individual floor panels.

To evaluate the effect of vibrations on a building, measurements should normally be made on the foundation or on the ground close to the building on the side facing the road. Vibration sensors should be mounted using methods that can faithfully transmit to the transducer the actual motion of the ground or building components over the frequency range of interest. If the mounting method is suspected of distorting the motion, alternative methods should be tested.

The degree of detail required in the analysis of the vibration signals depends on the nature and purpose of the investigation. For a preliminary evaluation, it might be sufficient to find the peak of the vibration signal and to determine the predominant frequency of vibration by counting the number of negative and positive peaks in a given time interval. For an in-depth evaluation, advanced analysis methods are necessary, such as one-third-octave frequency band analysis, frequency-weighting according to established human response curves, and spectral analysis.

Effect of Vibrations on People

Building vibrations caused by road traffic are not a health and safety concern; they are more a problem of annoyance. Vibrations may be unacceptable to occupants because of annoying physical sensations produced in the human body, interference with activities such as sleep and conversation, rattling of window panes and loose objects, and fear of damage to the building and its contents. Experience has shown that people living in houses are likely to complain if vibration levels are only slightly above the perception threshold, the major concern being fear of damage to the building or its contents. The tolerance level varies widely from person to person and from area to area.

The International Organization for Standardization and several countries (not including Canada) have published standards that provide guidance for evaluating human response to building vibration. The standards deal mainly with continuous and intermittent vibration such as that induced by machinery and pile driving, and impulsive vibration such as that induced by blasting. The standards are not clear about how to evaluate bus and truck vibrations, which have relatively short duration and complex amplitude characteristics. Alternative evaluation methods have been developed recently by IRC researchers based on their extensive measurements of traffic vibrations at several complaint sites.[3]

Potential for Building Damage

House owners may complain about damage induced by traffic vibrations, such as cracks in walls and ceilings, separation of masonry blocks, and cracks in the foundation. However, vibration levels are rarely high enough to be the direct cause of this damage, though they could contribute to the process of deterioration from other causes. Building components usually have residual strains as a result of uneven soil movement, moisture and temperature cycles, poor maintenance or past renovations and repairs. Therefore small vibration levels induced by road traffic could trigger damage by “topping up” residual strains. Consequently it is difficult to establish a vibration level that may cause building damage and, therefore, controversy continues to surround the issue. In some cases, when a building is subjected to vibration for many years, fatigue damage (i.e., that caused by repeated loading) may occur if the induced stresses in the building are high enough. In addition to damage caused directly by vibration, indirect damage may result from differential movements caused by soil settlement due to densification. Loose sandy soils are particularly susceptible to densification when subjected to vibration.

Several countries have adopted standards for evaluating the effect of vibration on buildings. No such national standards exist in Canada, but some provinces have adopted guide values for vibration induced by blasting. The most stringent vibration guide value specified in published standards for damage to houses is more than 30 times the human perception level. Occupants would therefore find potentially damaging vibrations to be extremely annoying because of their very high level. In a recent IRC study of vibrations induced by buses in houses at complaint sites in Montreal, vibration levels were found to be significantly lower than the most stringent guide value.[1]

Standards for evaluating human response to vibration levels

- ISO 2631/2 (1989), International Organization for Standardization
- ISO 8041 (1990), International Organization for Standardization
- BS 6472 (1984), British Standards Institution
- ANSI S3.29 (1983), American National Standards Institute

Standards for evaluating the potential for building damage

- DIN 4150 (1984), Deutsches Institut fuer Normung
- SN 640 312 (1978), Association of Swiss Highway Engineers
- BD 7385 (1993), British Standards Institution
- Report No. 8507 (1980), U.S. Bureau of Mines (blasting-induced vibration)
- Publication No. NPC-119 (1978), Ontario Ministry of the Environment (blasting-induced vibration)
- ISO 4866 (1990), International Organization for Standardization

Suggested Solutions and Preventive Strategies

Solutions and preventive strategies that have been suggested to reduce vibration to an acceptable level include periodic maintenance of road surfaces, control of traffic flow and speed, improvement of the road structure, soil improvement, sufficient distance between roads and buildings, screening of vibration using in-ground barriers, and building isolation systems. Some of these measures have proven to be effective.

Maintenance of the road surface (for example, levelling manhole covers, patching potholes and applying a new pavement overlay) is the most economical and effective remedial method. However, it is usually a short-term measure; for example, cracks and defects in the original pavement reappear in the overlay. Therefore, roads may have to be maintained more frequently than normally required for good rider comfort, safety and appearance. This will not always be feasible because of the high cost. Reducing speed limits and restricting heavy vehicles, while effective remedial measures, are usually difficult to enforce.

Experimental and theoretical evidence indicates that improving the structure of the road by increasing its thickness and stiffness is not effective for reducing vibration levels in the predominant frequency range of traffic-induced vibration (Figure 4). On the other hand, improvement of the soil structure under roads using deep mixing techniques could reduce vibration levels.

Increasing the distance between roads and houses might be a practical strategy for planned developments. Where vibrations result from impacts with a pothole or crack in the road, and considering geometrical damping only, vibration levels could decrease by at least one-third for each doubling of the distance if the soil is homogeneous. Attenuation relationships are in most cases site-specific and therefore must be measured on-site to determine the necessary distance.

In-ground barriers are trenches that are either left open or filled with a material (such as bentonite or concrete) that has stiffness or density significantly different from that of the surrounding soil (Figure 5). These barriers could be effective since traffic vibrations are mainly transmitted by the soil in the form of Rayleigh waves, which propagate near the ground surface.

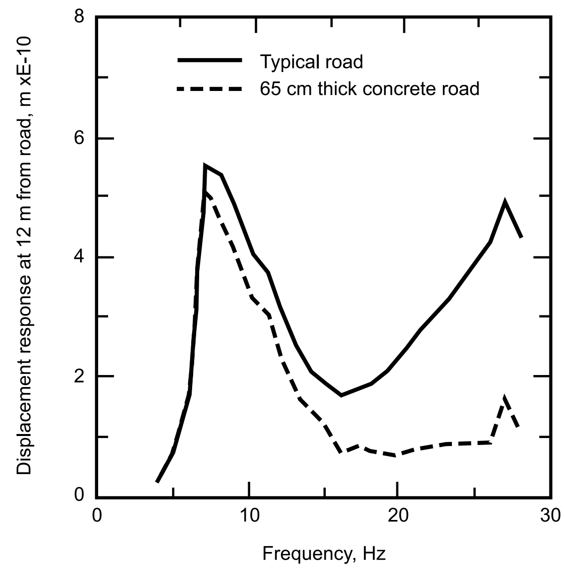

Figure 4. Effect of varying pavement stiffness on vibration levels. Stiffer road structures do not significantly decrease vibration levels at the frequencies that affect houses most (8 to 15 Hz).

In-Ground Vibration Barriers

Studies show that the depth of an in-ground vibration barrier has to be at least equal to one Rayleigh wavelength to achieve a significant reduction in vibration levels (a reduction factor of 0.25 is usually considered significant). In the case of traffic vibrations, very deep barriers would be needed (in excess of 10 m) because of the low-frequency nature of these vibrations.

Rayleigh waves

Rayleigh waves, which are the main carrier of traffic vibrations, are confined to a region near the surface of the ground that is roughly one wavelength deep. The ground motion induced by these waves has both horizontal and vertical components, which diminish with depth. Rayleigh waves that are induced by a point-like source on the ground surface, e.g., a vehicle striking a pothole, have cylindrical wave-fronts and are therefore attenuated much more slowly than shear and compression waves, which have hemispherical wave-fronts.

Attenuation mechanisms for ground vibrations

- Geometrical spreading:
  $A_2 = A_1 (r_1 / r_2)^n$
  $n = 1/2$ for surface waves
  $n = 1$ for body waves
- Material damping (soil friction)
  $A_2 = A_1 \exp [\alpha (r_2 - r_1)]$

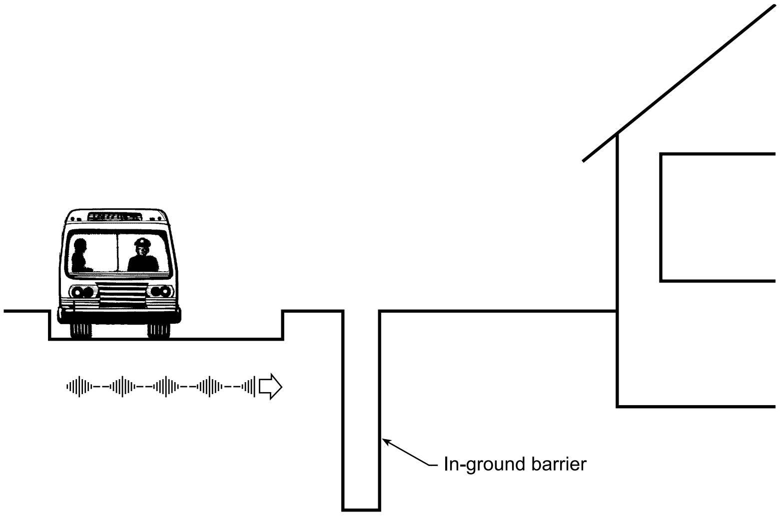

Figure 5. Schematic illustration of an in-ground vibration barrier

However, trenches may be too costly for situations involving houses. They could perhaps be justified for larger buildings with strict vibration limits, such as operating theatres of hospitals or high-tech factories with sensitive processes.

An economical alternative to trenches in a residential area could be a row of lime or cement piles in the right-of-way adjacent to the road. Such piles are constructed in situ by mechanical mixing of the soil with either quick lime or ordinary cement. The piles could have a diameter of 0.5 to 1 m and a depth of 15 m. However, the effectiveness of such pile-walls in reducing traffic vibrations has not yet been demonstrated.

The use of building isolation systems — for example, mounting the building on springs — is not effective for houses because of the predominantly low-frequency range of vibrations induced by road traffic. Unlike multi-storey buildings for which isolation systems have been successfully used to reduce subway-generated vibrations, typical houses do not have the necessary mass to induce the required deflections in isolation materials. The cost of installing isolation systems under existing buildings is prohibitive.

Summary

House owners are likely to complain about traffic vibrations if the levels are only slightly above the perception threshold, the main concern being fear of damage to their property. Building damage may occur but it is unlikely to be caused solely by the vibrations themselves. Reducing vibrations to an acceptable level could be difficult and expensive. For existing buildings, the most practical remedial measure is road maintenance. For new developments, increasing the distance between buildings and roads, improvement of soil structure, and in-ground pile barriers could prove effective.

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