TRAFFIC-INDUCED VIBRATION

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Vibration generated by highway traffic is a significant form of environmental pollution that has not been studied as comprehensively as noise pollution. Vibration sources and the mechanisms of vibration propagation and attenuation must be better understood before uniform criteria for vibration pollution and corrective measures can be established. The theory of ground-borne vibration provides considerable insight into the nature of traffic-induced vibration. The relevant theory and associated experimental data have not heretofore been put into a form useful to highway engineers and transportation scientists not trained in the problem area. The highway irregularity spectrum is the most important cause of vibration. The Rayleigh wave is of primary importance to traffic-induced vibration assessment. Significant structural damage from traffic-induced vibration is rare. However, human response to vibration is both physiological and psychological, and humans often classify vibration as unacceptable at levels lower than those that cause structural damage. The nature of the long wave lengths of traffic-induced vibrations makes it unlikely that attenuation measures such as trenches will be successful. Indications are that careful maintenance of the highway will be the most effective vibration preventive and that special abatement measures will be used only where complaints have occurred.

•CONCERN for the environment has heightened interest in all forms of pollution. A significant form of pollution, but one for which widely accepted criteria do not yet exist, is vibration. The study of vibration and the effects of vibration on man, equipment, and structures has long been a topic of investigation by physicists, engineers, geophysicists, architects, and human factors specialists. These investigations have considered vibration sources, transmission, propagation, and attenuation; characteristics of vibration received; and criteria relating vibration received to assessment of acceptable vibration limits. The ultimate value of any vibration investigation is the characterization of vibration impacts and the relation of their characteristics to the criteria for acceptable limits. In human response to vibration, the appropriate criteria relate vibration levels and spectra to human levels of perception, irritation, and physical discomfort; in building response, they relate vibration levels and spectra to architectural and structural damage. Concern has been growing over noise and vibration from various transportation sources because of the trend in increasing vehicle use and weight (thus, in increasing vibration) required to transport people and freight in our society. The major source of transportation in the United States is the highway, and, for the sake of convenience, buildings are normally located as close to highways as possible. Thus, vibration from roads and highways has become a growing source of concern, complaints, and litigation.

Although the noise and vibration from transportation systems have long been recognized as having adverse effects on the environment, the past analyses and abatement of environmental vibration have been relatively slight compared with recent noise abatement efforts by government and private organizations. Public interest in the vibration problem, however, already appears quite significant and is increasing. In a survey conducted by the Michigan Department of State Highways (1), vibration near I-75 was cited as bothersome more than two-thirds as often as noise. Public concern is further

reflected by the increasing frequency of litigation associated with environmental vibration [e.g., Tompkins v. State of New York, Pueblo v. Muce (Colorado), Coltin v. Anderdink (California)], despite an absence of federal or state environmental vibration regulations. Local ordinances, however, either have included vibration under tort trespass and general nuisance categories or are in the form of specific statutes dealing with vibration intrusion.

Originally, special issues such as sonic booms and blasting aroused considerable public interest about environmental vibration, which is now most frequently associated with highways because of their expanse and their proximity to the public. Research on vibrations from highways is now being sponsored by the Federal Highway Administration as well as by the governments of Great Britain, Czechoslovakia, Japan, and Norway. This research centers on the physical aspects of vibration generation and propagation for soil-transmitted stresses from vehicle-roadway interaction, airborne infrasonic pressure waves, and the resulting vibration produced in nearby structures. Research pertaining to other areas of the vibration problem has been extensive and plentiful (over 1,500 published studies related to human subjective response to vibration have appeared since 1830) but remains largely inconclusive.

Never before have the following been thoroughly analyzed: (a) traffic flow on highways as a source of vibration; (b) the transmission, propagation, and attenuation behavior of traffic-induced vibrations in relation to the complex geology of roadbeds near buildings; (c) the relationship of vibration levels to structural response, fatigue, and damage; and (d) the relationship of vibration levels and spectra to human perception, irritation, discomfort, and anxiety. The interdependence of these parameters is shown in Figure 1 and is discussed below.
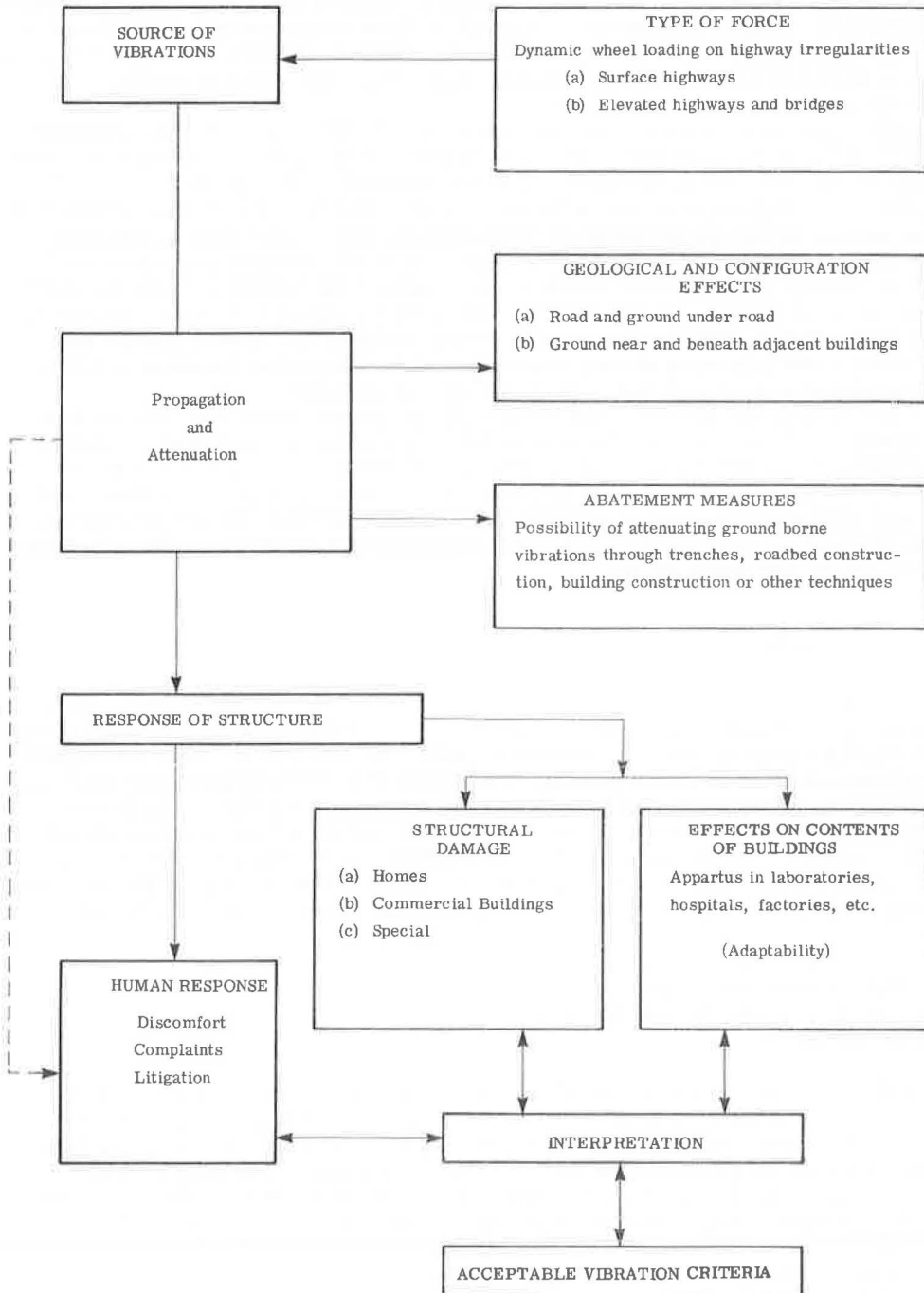

VIBRATION SOURCES

Traffic-induced vibrations have the time-varying forces of the tires of vehicles pressing on the highway as a primary source. The converse problem of the vibration of the vehicle itself due to the spectrum of irregularities in the highway has been well studied. The vibrations resulting from the passage of vehicles of various weights over highway irregularities can presumably be characterized in terms of a spectrum that is the product of the forcing function spectrum from the vehicles times the irregularity spectrum of the highway. A primary concern is to find the proper forcing function spectrum from vehicles as a function of their specific characteristics. An additional source of vibration is infrasonic sound. The following is a breakdown of vibration sources:

1. Irregularities in pavement profile,
2. Internal vehicle vibrations,
3. Changes in roadway impedance, and
4. Infrasonic sound.

The most significant vibration excitations are attributable to the passage of vehicles over irregularities of the pavement profile, commonly resulting from expansion joints, manhole covers, differential settling of pavement slabs, and potholes. The resulting impulsive forces on the pavement, in turn, excite oscillations in the vehicle itself (which, eventually, tend to aggravate the roughness of the pavement). Thus, the variation in forces between the tire and the road after an encounter with an irregularity is a function of the irregularity as well as vehicle speed, mass, and suspension.

Whiffin and Leonard (2) and Frydenlund (3) conducted experiments to measure the vibration generated during the passage of vehicles of various masses and velocities over ≤100-mm-high ramps placed in various pavements and soils. Their results indicate that the size of the irregularity (height of the ramp) as well as vehicle mass had pronounced effects on ground vibration. Parameters such as vehicle speed (tests were conducted at 30 and 50 km/h) and pavement thickness, however, had little effect. Figure 2 shows Frydenlund's results. These results are also substantiated by Sutherland's in situ study (4) of seismic vibrations caused by trolley cars introduced into Winnipeg,

Figure 1. Interdependence of parameters of traffic-induced vibration.

SOURCE OF VIBRATIONS

TYPE OF FORCE
Dynamic wheel loading on highway irregularities
(a) Surface highways
(b) Elevated highways and bridges

Propagation and Attenuation

GEOLOGICAL AND CONFIGURATION EFFECTS
(a) Road and ground under road
(b) Ground near and beneath adjacent buildings

ABATEMENT MEASURES
Possibility of attenuating ground borne vibrations through trenches, roadbed construction, building construction or other techniques

RESPONSE OF STRUCTURE

STRUCTURAL DAMAGE
(a) Homes
(b) Commercial Buildings
(c) Special

EFFECTS ON CONTENTS OF BUILDINGS
Appartus in laboratories, hospitals, factories, etc.

(Adaptability)

HUMAN RESPONSE
Discomfort
Complaints
Litigation

INTERPRETATION

ACCEPTABLE VIBRATION CRITERIA

Manitoba, and Bata's study (5) of assorted vehicles traveling on cobblestone roadways near medieval structures of historical interest.

Consequently, it has become important to characterize both the highway pavement irregularities and the frequency responses (i.e., the suspension and damping) of highway vehicles. Various instruments, such as the roughometer and the profilometer, have been developed to characterize roadway irregularities by actual measurement, and the frequency responses for trucks and passenger cars have been determined both analytically and and experimentally. The critical frequencies of highway vehicles are approximately 1.5 Hz for body oscillations, 10 Hz for rear-axle oscillations, and 12 Hz for front-axle oscillations. Other internal vibrations of the vehicle from slightly out-of-balance forces are of secondary importance because of their higher frequencies and efficient attenuation of modern suspension systems. Many other variations in the dynamic forces of vehicles due to acceleration and braking (as evidenced by the distortion of pavement profiles at intersections), tire stiffness, and the negotiation of curves remain to be studied.

A dynamic disturbance is also generated by the motion of a steady vehicle load as it passes over changes in road impedance (i.e., resistance to motion) typically associated with bridges and culverts. This is because, although the induced force is independent of road impedance, the power transmitted into the roadbed increases as the road resistance decreases (and increases as the wheel impedance increases). At the low frequencies pertaining to ground vibration (<20 Hz), the impedance of the roadway is in agreement with the spring constant determined by the subsurface below the pavement and the bending stiffness of the pavement. The dynamic coupling effect of the interaction of vehicles with bridges has been discussed by Popescu (6), who has shown that the commonly used bridge design criteria yield incorrect results when these effects are estimated. Figure 3 shows some of Popescu's results.

Finally, the exhaust pulse (and sometimes the pressure arising from the bow wave of passing vehicles) will transmit significant infrasonic sound to the soil or directly to the structures. Although this type of excitation does not normally produce sufficient pressure, when compared with typical wind pressures, to cause structural damage, the pressure waves impinge on large areas of transduction and cause audible vibrations in windows and frames.

VIBRATION PROPAGATION AND ATTENUATION

The fluctuating dynamic forces applied to the road surface by the wheels of moving vehicles generate stress waves that are propagated through the roadbed construction into the subsoil. (One of the functions of road construction is to spread the wheel loads so that the stresses applied to the soil subgrade are small and are only a fraction of that applied to the road surface). The geological characteristics of the soil, rock, and subterranean structures between the highway and nearby structures determine the paths and intensities of vibration propagation as well as the dispersive and dissipative properties. In general, soil is a nonlinear, thermoviscoelastic medium that can be layered, non-homogeneous, and anisotropic. Fortunately, a considerable understanding of vibration is possible without a precise theoretical description of the soil. Many soil properties, such as blastability, ripability, scraper loading characteristics, and bearing capacity, are already of concern to highway engineers in the determination of engineering properties.

Excitation of Subsoil

Transmission of vibration to the subsoil is complicated in practice because road construction has a layered configuration and because many of the materials used to build flexible roads are deliberately chosen to be absorptive and have elastic moduli that fall significantly as the road temperature rises. Furthermore, these materials are viscoelastic and have complex moduli that depend on the magnitude of the local stresses and the rate of loading.

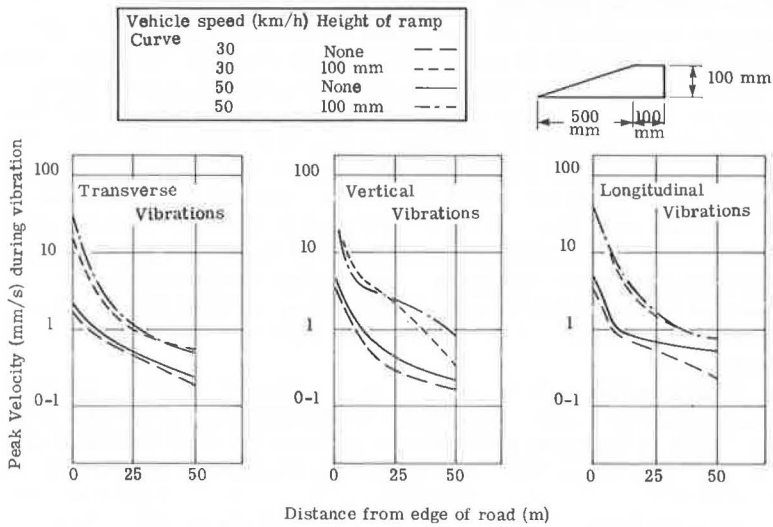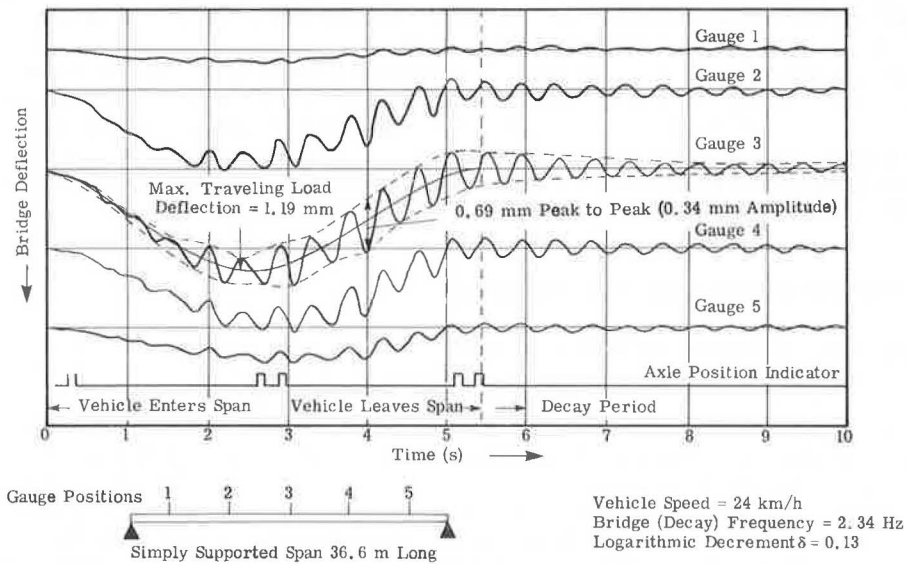**Figure 2. Effect of vehicle speed and ramp height on seismic vibrations.**

Curve	Vehicle speed (km/h)	Height of ramp	
	30	None	— —
	30	100 mm	– – –
	50	None	———
	50	100 mm	—·–·—

100 mm

500 mm   100 mm

Peak Velocity (mm/s) during vibration

Transverse Vibrations

Vertical Vibrations

Longitudinal Vibrations

Distance from edge of road (m)

Figure 3. Bridge deflections.

Bridge Deflection

Gauge 1

Gauge 2

Gauge 3

Max. Traveling Load Deflection = 1.19 mm

0.69 mm Peak to Peak (0.34 mm Amplitude)

Gauge 4

Gauge 5

Axle Position Indicator

← Vehicle Enters Span   Vehicle Leaves Span →   ← Decay Period

Time (s)

Gauge Positions   1   2   3   4   5

Simply Supported Span 36.6 m Long

Vehicle Speed = 24 km/h
Bridge (Decay) Frequency = 2.34 Hz
Logarithmic Decrement δ = 0.13

A complete treatment of the theory of the complicated viscoelastic properties and layering that correspond to a roadbed has not yet been achieved. It is likely that treatment of the properties of the roadbed as a pseudohomogeneous medium that is part of the source will constitute the most effective approach. This treatment is certainly feasible when the coefficients for propagation and attenuation are obtained from experimental data. The roadbed can be rather simply included in the source by using composite attenuation coefficients like those that exist for earth materials. Given such an overall factor, multiplying the source does not represent a significant deviation from a derivation using first principles because it would be possible to incorporate an overall attenuation factor in the forcing function to account for the absorption and cushioning effect of the tire and suspension of the vehicle. Thus, one possible characterization of the source would include three critical parameters: the distribution of the flow of vehicles, the spectrum of irregularities in the highway, and the attenuation factor for the roadbed.

Types of Waves

There are four types of waves relevant to the vibrations experienced by structures near highways:

1. Longitudinal or compressional body, p-waves;
2. Shear or transverse body, s-waves;
3. Surface or Rayleigh, r-waves; and
4. Boundary or interface, b-waves.

The p-waves and s-waves are collectively known as body waves, which radiate into the entire half space of the soil, but r-waves, such as water ripples, are confined near the surfaces. The b-waves (e.g., refraction arrivals and Love and Stoneley waves), which are similar to r-waves, occur only if layered media are present and only if the shear moduli of the underlying layer are greater than those of the overlying layer.

The geometric attenuation, or spreading, of body waves is 6 dB per doubling of distance (dd) for a point source and 3 dB/dd for a line source. For r-waves, it is 3 dB/dd for a point source and vanishes for a line source. The reduced geometric attenuation of r-waves and the fact that for surface excitations the partition of energy into p-waves, s-waves, and r-waves is approximately 1:5:14 indicate that r-waves are of primary importance to the ground vibration problem. Figure 4 shows the behavior of r-waves for different values of Poisson's ratio ν, which is the ratio of the s-wave and p-wave speeds.

The r-wave is a nondispersive wave polarized in the vertical plane parallel to the direction of propagation. Its propagation velocity is approximately 95 percent of the s-wave velocity, which, in turn, is approximately 50 percent of the p-wave velocity (e.g., 1 km/s in clay). r-wave particle motion within a depth of one-fifth wavelength of the surface is a retrograde ellipse whose vertical axis is about twice as long as one horizontal axis. Below this depth, the particle orbit changes from retrograde to direct, and the orbit size decays exponentially below a depth of one-half wavelength at an attenuation rate (which depends on Poisson's ratio and the dissipation rate) of greater than 16 dB/wavelength.

The p-waves have an amplitude only in the direction of propagation; the s-waves have an amplitude transverse to the direction of propagation, i.e., verticle or horizontal. The r-waves have amplitudes in both the vertical direction and the direction of propagation. The important case of b-waves results when there is hard rock beneath the surface soil layer and where wave propagation is along the boundary. There is usually less attenuation than for s-waves, p-waves, and r-waves propagating through the soil. Sometimes there can be peculiar magnification effects at distances where the b-wave propagates down to the hard rock, moves across at a faster speed, goes back up to the surface, and arrives at the same time as either the s-waves, p-waves, and r-waves. The presence of boundaries causes reflected waves of mixed polarization. For example,

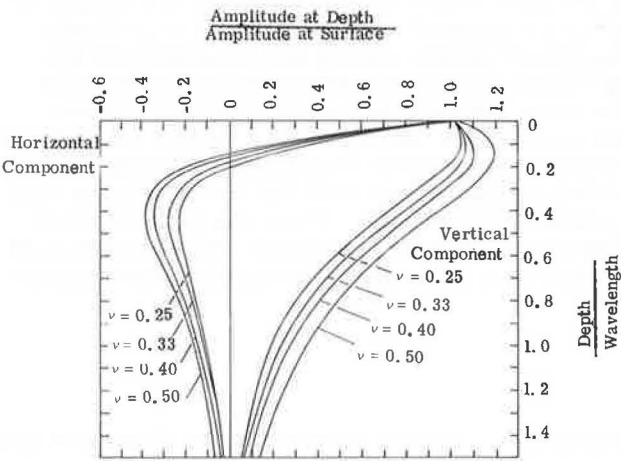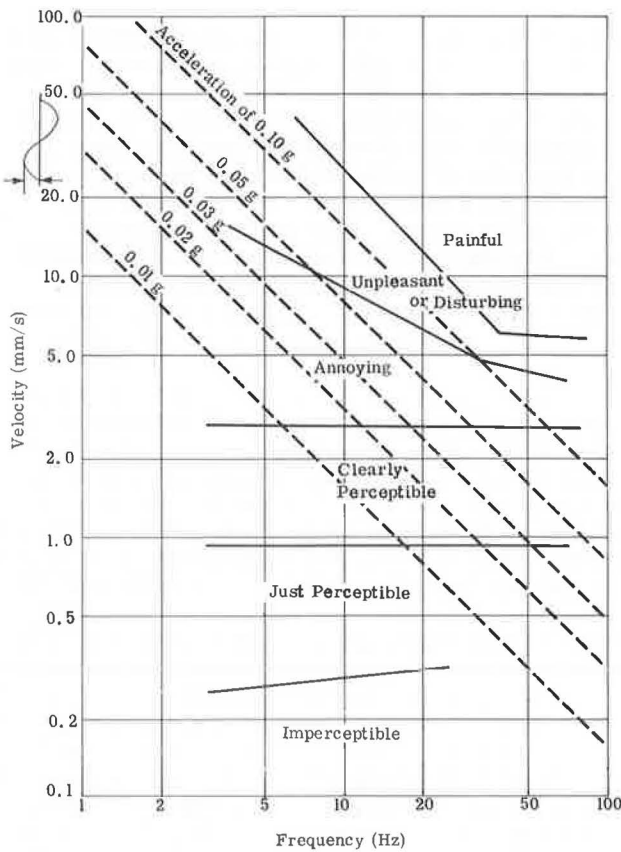**Figure 4. Dimensionless velocity versus depth ratios for Rayleigh wave.**

Figure 5. Human sensitivity to vertical vibrations.

pure p-waves or vertically polarized s-waves, which reflect from a horizontal boundary, cause a reflected wave with both polarizations.

The dissipation rate in earth materials is empirically determined to be proportional to frequency throughout the 1- to 20-Hz frequency range of interest (simple models of viscoelastic materials, however, yield an attenuation parameter proportional to the square of the frequency). Measurements of dissipation rates for typical materials are on the order of 3 dB to 30 dB per 100 ft (30 m) depending on frequency.

Thus, a vibration impulse will usually be detected at a distance as a slight compressional wave followed by two successively stronger waves that are separated by a relatively short interval. In addition, waves reflected from interfaces and air-coupled waves can be superimposed on this motion. The quantitative calculation of wave propagation has received considerable attention: Lamb's classic analysis of elastic waves in a homogeneous halfspace (7) and the treatment of inhomogeneities, anelasticity, and arbitrary interfaces by finite difference or finite element methods developed for the study of nuclear weapons effects. Analytical calculations, even for relatively simple models, rapidly become mathematically complex so that computer approximations must be used if precise results are desired. Such precision is generally not required for environmental problems, however, because other variables affect vibration.

STRUCTURAL RESPONSE

Any structure resting on soil possesses a fundamental oscillatory resonance, typically from 10 to 20 Hz, as well as higher bending or shear flexural resonances of structural components from 50 Hz on up into the audible range. These resonances are determined by the structure's construction, size, geometry, and, especially, the manner in which it is coupled to (i.e., in contact with) the ground. Much knowledge can be acquired from the analyses of structural response to earthquakes and blasting operations. Although the performance of detailed analyses of frequency response for most structures is a complicated problem, numerical methods using high-speed computers are now able to determine the structural vibration of buildings rather accurately, provided the nature of the excitations can be prescribed.

The effects of vibration on structures can be classified according to structural or primary damage, in which the integrity or safety of the building is in jeopardy, and architectural or secondary damage (such as plaster cracking), in which nonessential elements of a building are damaged. Accelerations above 0.1 g (or 0.98 m/s^2) at frequencies above 3 Hz and velocities above 50,800 μm/s (or 2.0 in./sec) at frequencies below 3 Hz are currently considered to be unsafe for buildings by the U.S. Bureau of Mines. The vibrations related to normal highway operations are usually unable to cause structural damage. When combined with other natural stresses such as the variation in temperature and humidity and the differential settling of the foundation, highway-induced vibrations may well be able to initiate or aggravate architectural damage.

HUMAN RESPONSE

Vibration produces human response through three methods: mechanical motion, vestibular response, and psychological factors. Mechanical motion includes the movement of the various portions of the body in relation to a stationary external location and adjacent portions of the body. The motions are produced in response to vibrational excitement of any part of the body. However, for the situations important to the traffic-induced vibration problem, the excitation should be considered as being applied to either the feet or the back side of the body. That is, emphasis should be placed on vibration situations experienced by the typical person when standing, sitting, or lying down at home or work.

Psychological responses to vibration are displayed in people's attitudes, feelings, and work performance. Depending on their background, they may like, dislike, or be indifferent to a given vibration. These effects may be direct responses to the vibration

or may involve emotional experiences and associations. The subjective response produced can be difficult to measure quantitatively, but the personal reactions that are produced may be sufficiently extreme to require that they be considered in any analysis. At present, few data are available on the psychological response to long-term exposure to vibration. Qualitatively, however, there appears to be a great effect present in the area of fatigue. Goldman and von Gierke (8) state that continuous exposure to vibrations only slightly above the level of human perception leads to irritation and fatigue.

Human tolerance is most widely used when vibration levels are interpreted. Tolerances curves such as shown in Figure 5 as a function of velocity and frequency are often used to determine the relative levels of vibration that are sustained and accepted as part of the environment. For traffic-generated vibration these curves are not necessarily sufficient, and a measurement of the intrusiveness of the vibration must be considered. The intrusiveness of traffic is the greatest in the home, where it is felt that traffic noises are out of place and more annoying.

The effect of vibrations on humans is a multifaceted problem involving both physiological and psychological responses (the pathological response involving illness is not experienced with environmental vibrations). It has been determined, mostly from aerospace research, that certain frequencies excite resonances in specific organs or organ groups in the human body. These resonant frequencies are, depending on the position and muscle tension of the body, 3 to 5 Hz for the thorax-abdomen system, 2 to 3 Hz for the shoulder and head, 20 to 30 Hz for the head alone, and 2 to 12 Hz for the whole body. All are well within the frequency range of highway-generated vibrations.

Furthermore, the cutaneous (vibrotactile) receptors and mechanoreceptors (somatic detectors) are able to perceive accelerations of 0.01 g at frequencies between 1 and 35 Hz, which is below the levels causing structural damage. This low threshold (or high sensitivity) to vibration and the instinctive fear of ground motion in all animals, including man, frequently lead to subjective or psychological responses to vibration as unacceptable at levels at which structural damage is not possible. Annoying effects that are frequently visually or audibly perceived, such as the motion of hanging fixtures or the rattling of dishes or windows, can result from secondary resonances even though the structural vibration levels are not directly perceivable. There is a great deal of literature about the subjective responses to vibration and subjective rating criteria. However, no universal criterion or metric value for subjective ratings of vibration has been established because of the large number of experimental parameters, nonuniform experimental methodology, and lack of understanding of intermodal factors (e.g., traffic noise), which may either mask or combine synergistically with vibration. (Vibration criteria based on the best available data, however, have been proposed by the International Organization for Standards).

CONTROL AND ABATEMENT MEASURES

Whiffin and Leonard (2) and Bata (5) point out that maintenance of a smooth highway with the minimal number of irregularities due to potholes, slab misalignments, and undulations is one of the most effective controls for vibration. At sites that are particularly sensitive to vibration, speed limits may have to be reduced, large vehicles excluded, or perhaps, in extreme cases, all traffic excluded. Near the highway, trenches or steel sheet piling may be introduced to lessen vibration impacts. Such techniques do not, however, hold much promise because of the nature of long wavelengths of traffic-induced vibrations. Probably most promising is isolation of the roadbed or nearby buildings with an insulating shell of sand or some other material. Full-scale experiments must be conducted to quantify the effectiveness of any proposed control or abatement technique.

SUMMARY

Traffic-induced vibration appears, at least under certain circumstances, to be a significant pollution problem. Further research is required to characterize the propagation

and attenuation characteristics within the complex geological and structural surroundings in which complaints are likely to occur. A better understanding of the propagation and attenuation mechanisms of traffic-induced vibration, achieved through both full-scale experiment and theory, will allow the design and implementation of effective control and abatement strategies. Research must also be conducted to formulate vibration criteria to quantify impacts and to determine when corrective measures need to be instituted.

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