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THE IMPLICATIONS OF STRUCTUREBORNE NOISE AND VIBRATION FROM URBAN RAIL SYSTEMS ON SENSITIVE BUILDINGS

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1 INTRODUCTION

In recent years there has been an increasing awareness of and concern for the quality of the environment in general and in the implications of noise and vibration in particular. Much of this has been directed towards the development of transportation systems, especially air transportation and roads, but less attention has been directed towards tracked transit systems, primarily because few new rail networks have been proposed and existing tracks have been established for many decades. Interest in the environmental implications of rail systems is now much more widespread in Europe for several reasons, particularly the development of new over- and underground railways, limitations on land for development and the increased use of vibration sensitive equipment.

Whilst one of the most obvious environmental consequences of rail transport is airborne noise from overground tracks, both over- and underground rail systems generate significant levels of groundborne vibration, which can be perceived not only as vibration, but also as noise, re-radiated by building structures. Whilst legislation and accompanying calculation methods similar to those for road traffic are being introduced for airborne noise from railway operations (Noise Insulation (Railways and Other Guided Transport Systems) Regulations, Reference 1) such guidelines are not available for groundborne vibration effects. This paper considers the problem of groundborne vibration on sensitive buildings and reviews the guidelines for achieving appropriate levels of noise and vibration in sensitive buildings.

2 GENERATION AND PROPAGATION OF GROUNDBORNE VIBRATION

Groundborne vibration is generated by the interaction of the wheel and track. Any irregularities in either the wheel (eg flat spots), or the track (eg rail joints, junctions, points, etc) give rise to an increase in the impact of a point on the wheel with the rail and hence in the vibration level generated. The vibration is transmitted into the sleepers and rail fixings and, thereby, into the surrounding ground via the trackbed foundations, or the tunnel wall (Figure 1). The range of frequencies propagated by the passage of a train is generallly limited to the range 8Hz-250Hz. Within this range, vibration at approximately 10Hz is dominated by the vehicle suspension system, while at higher frequencies (above 50Hz) the rail-wheel interaction becomes the dominant mechanism.

The vibration then propagates through the ground in the form of surface, compression and shear waves. The shear and compression waves spread as three-dimensional wave fronts from a line source, such that the energy decays with increasing radial distance from the source. Attenuation of the surface wave is much less, as the propagation is two-dimensional and in the plane of the surface. Propagation is also controlled by the soil type and structure - clay, for example, gives rise to higher attenuation than sand, or chalk.

The vibration energy then enters a building via its foundations and is transmitted through the structure (walls, floors, ceiling). The energy within the building may then be perceived as a vibration, or re-radiated by the building surfaces as noise and is, in turn, affected by the structural response of the building. The vibration response of a massive building construction is significantly less than that of a modern, lightweight steel or concrete building, where structural resonances can occur at frequencies similar to those of the excitation due to the passage of a train (Figure 2).

Measurement studies of the vibration energy at building foundations have shown that peaks occur in the frequency range between approximately 8Hz and 12Hz and then at 50Hz to 80Hz (Figure 2). The former may be perceived as vibration, while the latter results in sound, generally heard as a rumble as the train passes near to the building.

3 PREDICTION OF VIBRATION LEVELS IN BUILDINGS

It is clear that the prediction of vibration levels in a building is complex. The energy generated by the source is a function of the train type and will vary with:

- train length
- unsprung mass
- axle weight
- speed
- wheel and track condition
- track type (continuous or jointed)

The subsequent propagation of the energy is affected by:

- track foundation
- track bed/soil interface
- soil type and structure
- soil/building foundation interface
- building response

A detailed theoretical, or even empirical, knowledge of all these parameters is unlikely and the prediction methodology relies on considerable simplifications. It is often necessary, or desirable, to determine as much empirical data as is practicable to assist in predicting the level of vibration in a new building from an existing railway, or in an existing building from a proposed railway, using calculation methods such as that by Ungar and Bender (Reference 2), which assumes that only compression waves are likely to be significant. The source vibration level (which can be measured or estimated) is subject to geometrical attenuation assuming cylindrical propagation from a line source, and attenuation due to the characteristics of the soil, which is a function of the wavelength, distance, a loss factor related to the soil type and the speed of propagation of the wave. Empirical loss factors, which are a function of the foundation type, are used to allow for the efficiency of propagation into the building. Propagation within the building can then be estimated, taking into account the likelihood of amplification which can occur in suspended floors.

The final vibration level can be converted to a sound pressure level using the simple relationship for a plane vibrating surface, which relates the velocity, the surface area and the radiation efficiency (0.1 below critical frequency, 1 above).

4 CRITERIA FOR ACCEPTABILITY

It has been shown that rail induced vibration results in the propagation of energy at frequencies between approximately 8Hz and 250Hz, with maxima occurring between approximately 10Hz - 12Hz and 50Hz 80Hz. Above approximately 20Hz, vibration displacement is so small that "feelable" vibration would not be apparent, but vibration can give rise to rattling of, for example, windows and ornaments on shelves. Large surfaces (such as walls, floors and ceilings) radiate energy as pressure waves and, above 20Hz, this can be detected as sound. The sensitivity of the human ear is such that it is primarily the energy above 50Hz that is heard as structureborne sound from railways.

Separate criteria are, therefore, necessary to determine the acceptability of vibration and noise from railways.

4.1 Vibration Criteria

Three types of criteria are relevant to the analysis of vibration response:

- human response criteria
- damage to buildings
- effects on sensitive equipment/instrumentation

4.2 Human Response

The human response criteria are governed by a consideration of comfort and annoyance of users of a building. Appropriate limits, based on the likelihood of adverse comment, in different types of building (residential or commercial) and for two time periods, day and night are provided in BS 6472 (Reference 3) and illustrated in Figure 3.

4.3 Building Damage

A British Standard defining criteria for levels of vibration above which building structures in the UK would have a finite probability of cosmetic damage due to vibration has recently been published (Reference 4). The criteria are related to building types and are presented as peak particle velocities (ppv, mm/s) within the frequency range 4Hz - 150Hz (Figure 4). Similar European Standards also exist, although these are based on building constructions appropriate to the countries of origin (Germany and Switzerland).

Measured and predicted levels of vibration velocity from train pass-bys have been shown to be sufficiently below these criteria at distances greater than 10m from the source, that building damage is generally considered unlikely.

4.4 Vibration Sensitive Equipment

The above criteria do not take into account the use of vibration sensitive equipment. Whilst there are no Standards defining suitable limits for such equipment, criteria developed by Gordon (Reference 5 and Figure 5), inter alia, as well as manufacturers' data, can be applied. It can be seen from Figure 5 that the limits recommended by Gordon are significantly below those determined for human perceptibility and that disturbance from train pass-bys at distances of up to 100m is possible. It is clear that special consideration must be given when considering the effects of new railways on nearby laboratory and similar buildings and the application of blanket criteria based on human perceptibility or building damage is not appropriate.

4.5 Structureborne Noise Criteria

There are no generally accepted Standards which define acceptable levels for structureborne noise, or, indeed, the parameters which should be used to define such levels. The only UK guidance is British Standard BS 8233 (Reference 6), a Code of Practice which gives recommendations for the control of noise in and around buildings. These are primarily related to speech interference and disturbance to occupants of buildings for a wide variety of uses. The possibility of nuisance from structureborne noise due to underground railway operations is briefly referred to, but no quantitative information is given.

In establishing criteria there are several factors which require consideration including:

- noise level parameters
- existing ambient noise
- building use
- engineering limitations
- financial implications

design aim
- inaudibility
- acceptability
- annoyance
- disturbance

In the absence of specific Standards, guidance can be sought from other sources. The American Public Transit Association (APTA) has published guidelines for maximum re-radiated noise levels in occupied buildings (Reference 7), which take into account the building type and, for residential buildings, the community area; the latter providing some allowance for likely external ambient noise levels (Tables 1 and 2):

Residences and buildings with sleeping areas				
Community area category		Single family L_{Amax} dB	Multi-family L_{Amax} dB	Hotel/motel L_{Amax} dB
I	Low density residential	30	35	40
II	Average residential	35	40	45
III	High density residential	35	40	45
IV	Commercial	40	45	50
V	Industrial/highway	40	45	55

TABLE 1: APTA criteria for residential and similar buildings

Special function buildings	
Type of building or room	Groundborne pass-by noise design goal L_{Amax} dB
Concert hall, TV studio	25
Auditorium, music room	30
Church, theatre	35
Hospital sleeping room	35 - 40
Courtroom	35
School, library	40
University	35 - 40
Office	35 - 40
Commercial	45 - 55

TABLE 2: APTA criteria for special function buildings

It is pertinent that these guidelines are similar to those accepted by the BRE (Reference 8).

London Underground Limited (LUL) has proposed a design aim for groundborne noise of 40dB L_{Amax}, measured using the slow response of the sound level meter. For sensitive buildings (eg reference libraries, lecture theatres, hospitals, churches and schools) it is proposed that a lower value may be appropriate, but no value is given. The criterion is clearly at the high end of the range proposed by the APTA.

A further example is the recent commercial and residential development of the Södra Station site in Stockholm, where the design aims were set at 30dB L_{Amax} for noise and $0.4m/s^2$ for vibration.

All the criteria quoted above are in terms of the maximum sound level, measured in dB(A). Other parameters can be used to quantify intermittent noise levels, such as L_{A1} (the sound level exceeded for 1% of the measurement period) and L_{Aeq}, the equivalent continuous sound level. The L_{Aeq} is becoming commonly accepted as a measure of transportation noise in Europe and has also been adopted for the assessment of airborne rail noise in the UK, following publication of the Mitchell Report (Reference 9) and the consequent Noise Insulation (Railways and Other Guided Transport Systems) Regulations. The L_{Aeq} is, however, particularly insensitive to the occurrence of short term events, especially when measured over an extended time period. This parameter may not, therefore, by itself, be an adequate descriptor to rate disturbance or annoyance due to train pass-bys. For this, the L_{max} can be considered more appropriate.

When measuring a parameter such as L_{max}, the response characteristics of the meter ("fast" and "slow") are an important factor in establishing the subjectively perceived maximum value. The response used when measuring parameters such as maximum, minimum and peak levels is important for interpreting the result in terms of subjective response, particularly when dealing with relatively short (100ms) transient signals such as occur in a train pass-by. Kryter (Reference 10) has established that the effective time response of the ear is related to the level of the intrusive noise above the ambient noise, or the threshold of hearing.

Where intrusive transient noise can only just be detected, the subjective response can be approximated by the "slow" meter response, whereas, when the sound is clearly audible, the subjective response is more closely related to the "fast" response. Work by Arup Acoustics has shown that, for typical underground train pass-bys, the L_{Amax} measured with a "slow" response can be 2dB - 4dB lower than that measured with the "fast" response. This represents a just perceptible change in sound level and can be significant when defining, or designing to meet, criteria. It is clear from these two factors that meter response time is important when assessing maximum level criteria and that, when noise from pass-bys is likely to be clearly audible, the "fast" meter response can be more appropriate.

It is a well established principle that the subjective response to intrusive sound is strongly related to the level of background noise on which it is imposed. Noise which exhibits distinctive characteristics (tonality, impulsiveness, intermittency, etc) also evokes a greater response than continuous broad-band sound. The APTA recommendations propose lower limits for "area categories" and more noise sensitive spaces, which may be loosely related to background noise levels. Current LUL proposals take no account of background noise and give no guidance to suitable limits for noise sensitive buildings.

In some buildings, the background noise can be easily measured in the frequency bands of interest, in others it can be defined by recourse to design background noise criteria using noise rating (NR) curves (Figure 6), or preferred noise criterion curves (PNC). Although these curves were initially developed for continuous noise sources and are principally used to define suitable levels of mechanical services (ventilation or air-conditioning) noise, the NR curves can have corrections applied for intermittent sources. The measured or predicted structureborne noise levels from train pass-bys can easily be compared with these curves to derive a qualitative judgement of the likely intrusiveness of the train pass-by.

This approach, which assesses the octave-band sound levels in the audible frequency range in which re-radiated structureborne noise from trains is significant, overcomes a particular disadvantage of the use of the overall, A-weighted sound level as a descriptor. The A-weighting does approximate to the frequency response of the human ear, but its suitability for rating noise with a distinctive low frequency content within a predominantly mid and high frequency background has been questioned. It considerably reduces the significance of low frequency energy (a weighting of -26dB is applied at 63Hz, the centre frequency of the octave band containing most of the audible energy from structureborne noise due to trains) and de-emphasises the actual subjective response to sound with negligible mid and high frequency energy.

These factors highlight a requirement for criteria which place a greater emphasis on the audibility of structureborne noise by taking into account its frequency content and the level relative to actual background noise levels.

4.6 Use of Frequency and Background Noise Dependent Criteria

The assessment of noise intrusion from road and rail transport to noise sensitive buildings (including offices, dwellings and auditoria) by relating the octave band noise levels to the background noise level (actual, or proposed as a design aim) has been used for some years by Arup Acoustics. With the increased use of urban sites close to major transport links and the commercial advantages of the development of "air-rights" buildings, such methods have taken on increasing prominence.

A criterion found to be successful for the protection of buildings against high levels of intrusive noise from trains has been to limit the amount by which the structureborne noise $L_{Amax,fast}$ can exceed the design mechanical services noise in the octave bands from 31.5Hz to 250Hz (Figure 6). A services noise rating of NR35 is usually suitable for cellular offices, NR30 for high quality offices and NR25-NR30 for conference rooms. Intrusive noise in theatres, auditoria and recording studios can be particularly disturbing, especially during quiet passages of speech or music and a lower rating (NR20 or less) can be an appropriate overall design aim, although other sources of intrusive noise should be taken into account when setting the criterion.

5 MITIGATION

Methods of mitigation of groundborne and structureborne noise for new buildings have been introduced above and clearly fall into two main areas:

- building isolation
- track isolation

Reduction of energy levels at source, by treating the rail/wheel interaction, offers limited scope at present, although it must be stressed that good maintenance procedures to minimise wheel flats and unevenness of the track are essential. It is also clear that the use of continuous welded track is advantageous, although breaks for signalling purposes are potential sources of relatively high vibration energy.

5.1 Building Isolation

Building isolation may be total or, if groundborne vibration levels are sufficiently low in areas more remote from the track, partial. Methods commonly used incorporate coil springs or resilient pads between the isolated structure and its non-sensitive supporting structure or the foundations. The junction between pile caps and columns, for example, provides a suitable interface. The building design must then ensure that this isolation is maintained throughout the rest of the structure. Resilient breaks must be provided between unisolated and isolated parts of the building, both in the design and the construction. Bridging of the isolation is all too easy when installing piped or ducted services and particular care must be taken to ensure that resilient breaks are not bridged by rubble and other building waste.

Building isolation is obviously only practicable on new buildings and does carry severe cost and design overheads. Recent examples have indicated costs of isolation to be typically 1% to 2% of total building cost, but, where the building is more complex, it can be as high as 5%.

5.2 Track Isolation

Several proprietary methods for track isolation exist, with varying degrees of effectiveness. The general principal is to provide a resilient interface between the rail and the ground, or the tunnel wall for underground railways.

Typical isolation methods include:

- resilient rail fastenings and track boots between the rail and sleeper (eg the "Cologne egg")
- resilient under-sleeper pads
- resilient ballast mats or springs between the track slab and the track foundation (floated slab)

Choice of isolation method and the characteristics of the resilient material requires a detailed knowledge of the criteria to be met by the isolation system, the likely propagation characteristics of the intervening ground and the likely response of the building structure. Much of this information is, of necessity, empirical, although there is an increasing amount of practical research data now available to assist in the design and selection process.

There are four main arguments in favour of track isolation:

- existing buildings can be protected
- new building costs can be reduced
- new building design is simplified
- the polluter pays

7 CONCLUSIONS

The points discussed above have become particularly relevant recently with the advent of new light rail systems in several cities in the UK and the proposals for CrossRail, the Jubilee Line and the Channel Tunnel Rail Link. The proposed London rail links are likely to affect hundreds of buildings adjacent to the planned routes, of which many will be particularly noise and vibration sensitive. These include the West End theatres (vital to the economy and life of London), recording studios, concert venues, hospitals and residential accommodation.

For many of these buildings, an overall criterion (eg 40dB $L_{Amax,\ slow}$) could result in a deterioration of the internal environment. Many London auditoria and studios are already affected by high levels of intrusive noise, particularly from rail systems. Whilst airborne noise can be controlled by relatively easily implemented methods, it is not possible to modify an existing building against structureborne noise. The only practicable control is at source, by the use of suitable track isolation techniques. Prevention of a worsening of the existing situation requires that new track systems be designed at the outset with effective noise and vibration control incorporated, where the tracks run adjacent to noise sensitive buildings. Where appropriate, existing tracks can then be improved (isolated as necessary) as part of a normal track maintenance programme.

The selection and installation of a cost-effective track isolation system relies on the setting of appropriate criteria, which take account of the frequency spectrum of the intrusive signal and the ambient noise conditions in the receiving space (existing or as a design aim). Without such a noise control programme, the quality of noise sensitive buildings cannot be brought up to, or maintained at, the standards appropriate to their use.

8 REFERENCES

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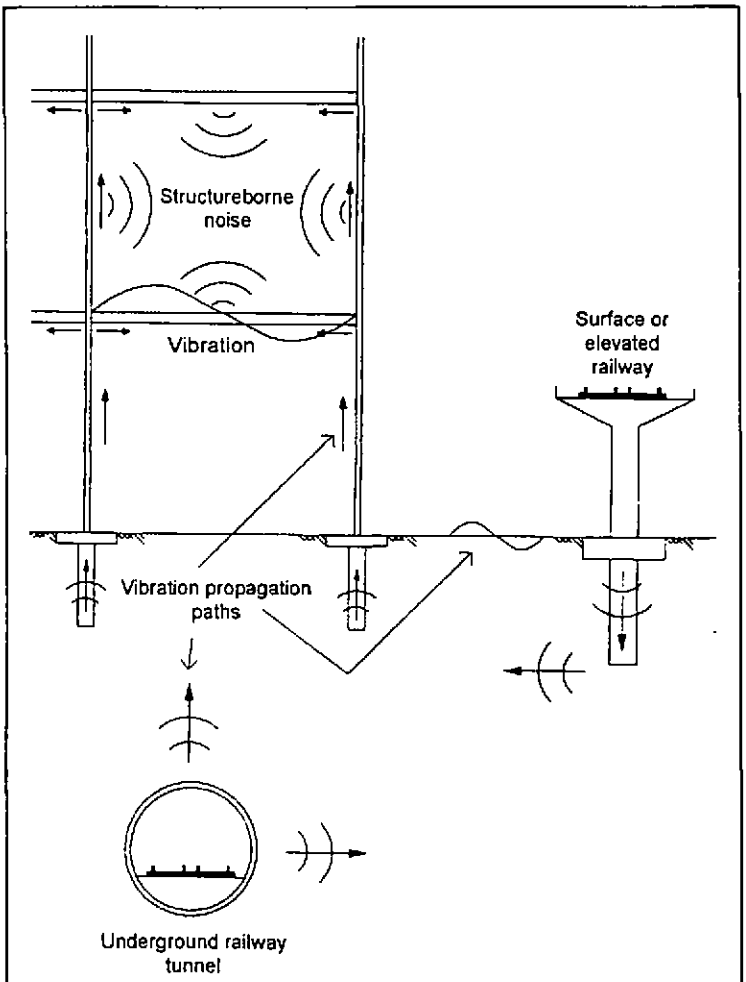


FIGURE 1: Groundborne propagation from railways

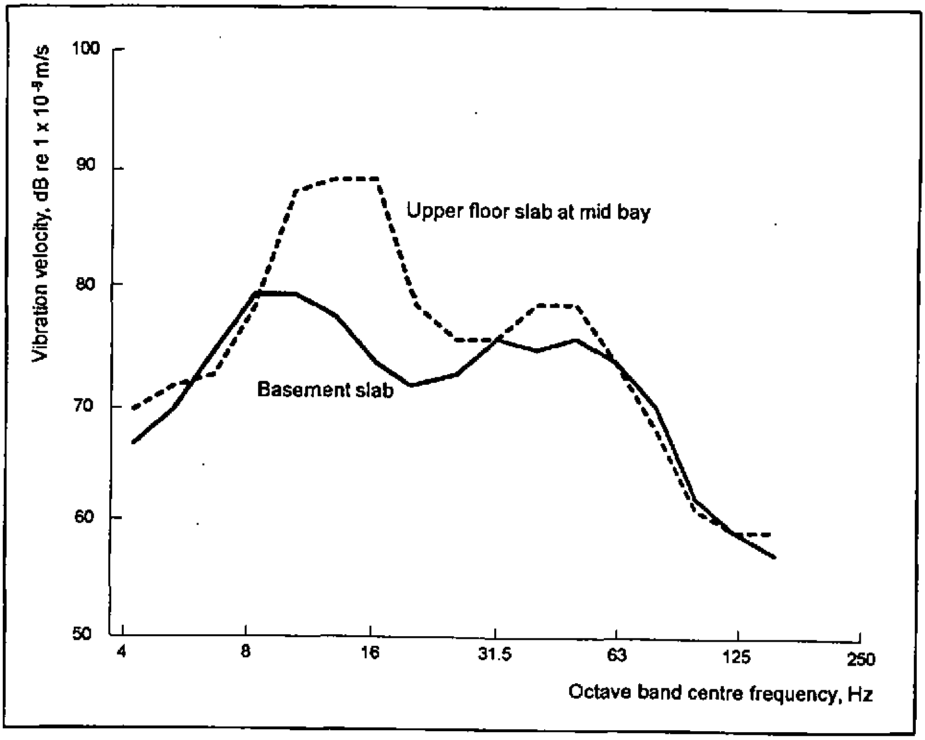


FIGURE 2: Typical vibration spectra from a lightweight concrete building during LUL train pass-by

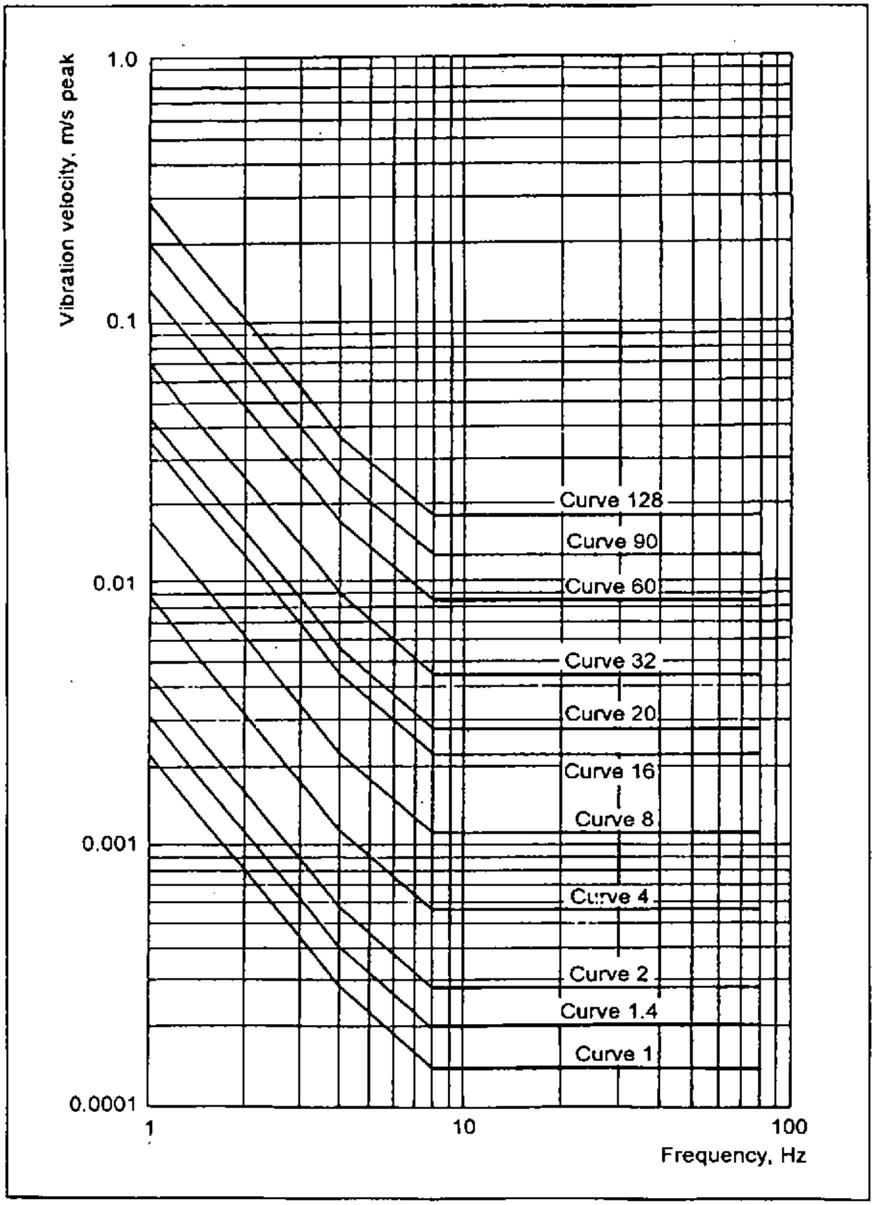
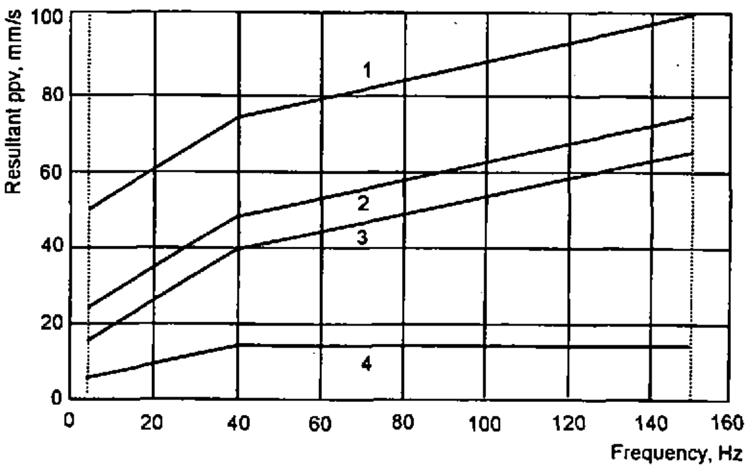


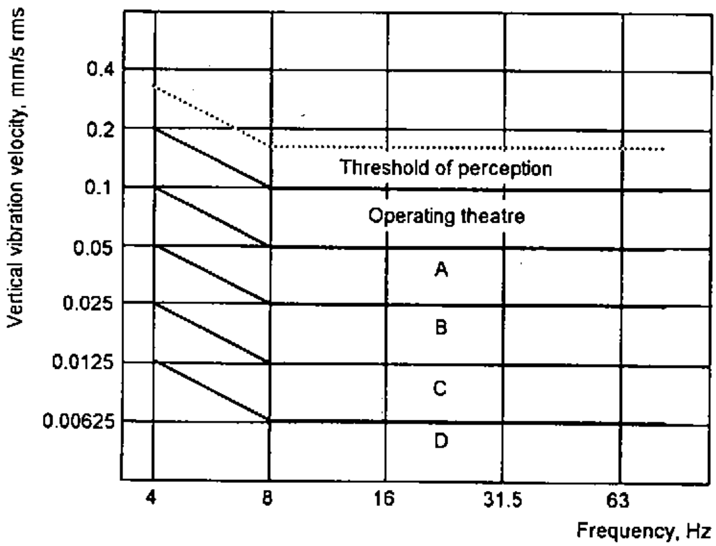
FIGURE 3: Vibration criteria for human exposure in buildings (z-axis) (BS 6472: 1992)



BUILDING TYPE:

1	Reinforced or framed structures Industrial or heavy commercial buildings
2	Un-reinforced or light framed structures, hard ground Residential or light commercial buildings
3	Un-reinforced or light framed structures, soft ground Residential or light commercial buildings
4	Sensitive buildings Unframed and in poor condition

FIGURE 4: Building vibration criteria above which cosmetic damage may occur (BS 7385: 1993)



SENSITIVE EQUIPMENT TYPE

A Probe test equipment, 100x microscopes

B 500x microscopes, aligners, steppers to 5μm geometries

C 1000x microscopes, aligners, steppers to 1.5μm geometries

D Steppers, E-beams to 0.3μm geometries, scanning electron microscopes to 50000x

FIGURE 5: Floor vibration criteria for sensitive equipment

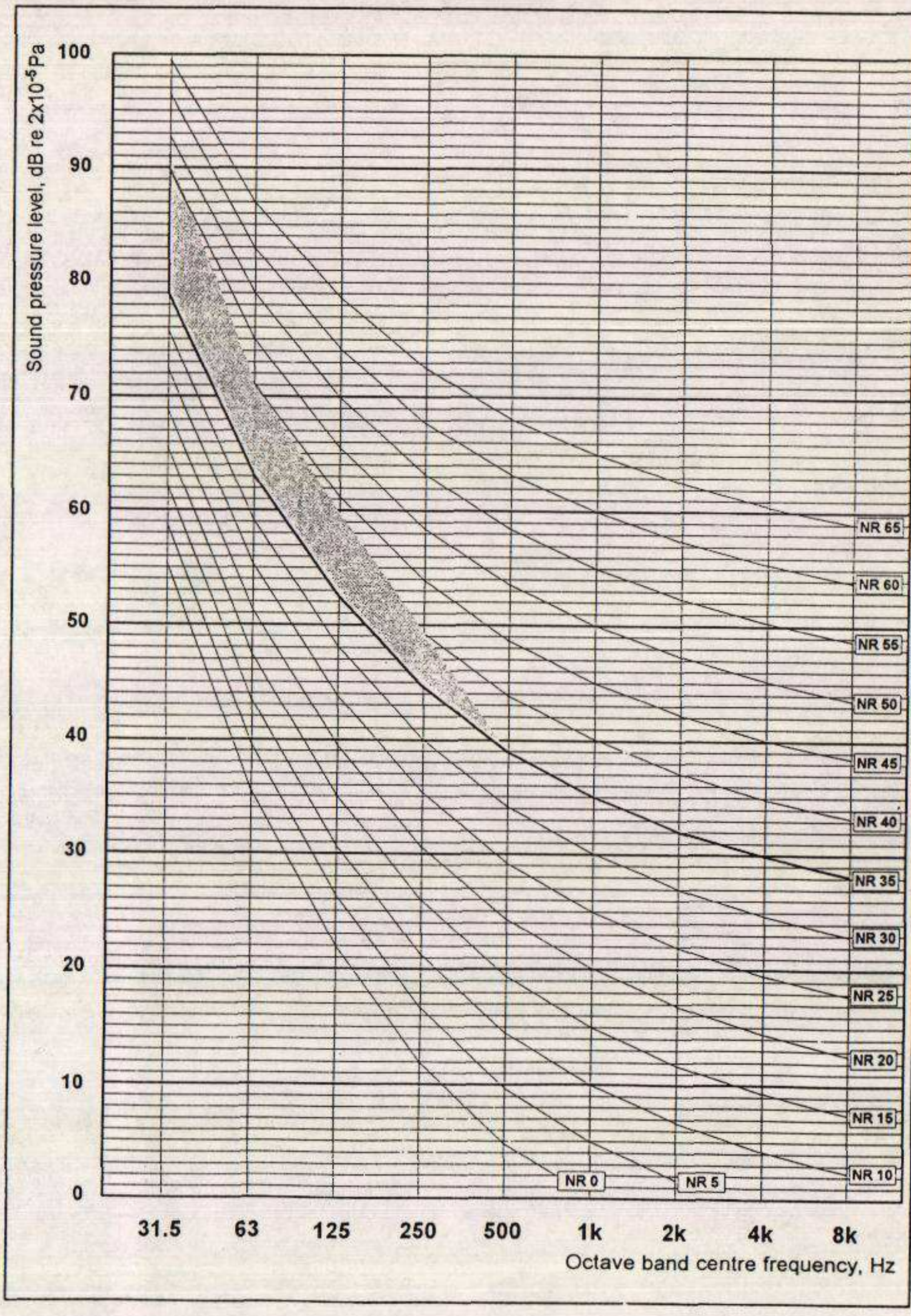


FIGURE 5: Noise rating curves, showing recommended design criterion for structureborne railway noise (NR 35)