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TRAFFIC INDUCED VIBRATIONS IN BUILDINGS

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ABSTRACT

Traffic vibration is a common source of environmental nuisance affecting residents. This report summarises TRRL studies of the effects of these vibrations on people, buildings and equipment and includes results from other relevant investigations. The first section describes the nature of the problem as revealed by questionnaire surveys and details the methods for predicting the degree of disturbance likely to be caused by both airborne and ground-borne vibrations. The effects of vibration on sensitive equipment and critical tasks are also considered. The second section reports on a number of investigations into the effects of traffic vibration on buildings. Studies included a fatigue test on a vacant property, comparisons of structural defects in houses exposed to high levels of vibration with similar properties exposed to relatively low levels, and case studies of heritage buildings adjacent to heavily trafficked roads. It is concluded that although traffic vibration can cause severe nuisance to occupants there is no evidence to support the assertion that traffic vibration can also cause significant damage to buildings. Lastly, possible methods for reducing traffic vibration nuisance are described.

1 INTRODUCTION

Traffic induced vibration in buildings is a common source of nuisance affecting residents and under certain circumstances degrading the performance of precision measuring equipment. The scale of the problem experienced by residents was indicated in a broadly based survey of environmental disturbances caused by road traffic (Morton-Williams et al., 1978). It was found that 37 percent of residents experienced traffic vibration and 8 percent were seriously bothered (ie bothered 'very much' or 'quite a lot'). Some interesting comparisons were made with other types of disturbance in this survey. For example, it was found that traffic noise was heard inside by almost everyone in the survey, but the percentage seriously bothered by traffic noise (9 percent) was similar to the percentage seriously bothered by vibration (8 percent). Thus although traffic vibration is only noticed by a minority of people it seriously bothers a similar number of respondents to traffic noise. Traffic vibration, therefore, represents a serious environmental disturbance affecting large numbers of people. For this reason TRRL has been engaged on a programme of research to find ways of assessing the effects of vibration, and methods of reducing its impacts. During the course of this work several reports and conference papers have been published. This compendium report summarizes the results of these studies and includes relevant information from the literature. The report updates and expands an earlier review of the subject area by Whiffin and Leonard (1971).

The first section of the report describes the nature of the disturbance as revealed by surveys and the methods that have been developed to predict the degree of disturbance from physical measures. The results should prove useful in assessing the environmental impacts of traffic management schemes or the construction of new roads. The second part of the report addresses the important issue of whether damage to buildings can be caused by exposure to traffic vibration. Many residents believe this to be the case and in particular there is concern that vibration from heavy vehicles is damaging heritage buildings which may be in a weakened state due to other causes (Civic Trust, 1970; Crockett, 1966). The report summarises a number of studies including a fatigue test in which a recently vacated house was exposed to high levels of simulated traffic vibration, and a series of case studies of heritage buildings located adjacent to heavily trafficked roads. Finally, possible methods to ameliorate the effects of airborne and ground-borne traffic vibration are described.

2 TYPES OF TRAFFIC VIBRATION

Passing vehicles can induce vibrations in buildings in two major ways. Low frequency sound produced by large vehicle engines and exhausts has dominant frequencies in the 50–100 Hz range corresponding to the fundamental firing frequency. Inside buildings, low frequency sound can excite the resonant frequencies of rooms by acoustic coupling through windows and doors. This may produce detectable vibrations in building elements particularly if they are light and flexible (Martin et al, 1978). High levels of vibration can be measured on window panes fronting heavily trafficked roads and this can give rise to annoying rattles (Watts, 1984). At the most exposed locations acoustically induced floor vibrations can become perceptible (Watts, 1987; Martin, 1978). However vibration levels in the hard structure of the building are much lower.

Ground-borne vibration has dominant frequencies in a lower frequency band, typically 8–20 Hz.

These vibrations are produced by the varying forces between tyre and road and can become perceptible in buildings if heavy vehicles pass over irregularities in the road near the properties. Both compression and shear waves are produced and their amplitudes and attenuation with distance depend on a number of factors including the soil composition and the nature of the geological strata. Since this vibration enters buildings through the foundations, the hard structure of the building is normally affected to a greater degree than is the case for airborne vibration. The principal component of vibration in the ground and at foundation level is in the vertical direction and this is readily amplified on suspended wooden floors on upper stories since the natural frequency is often close to that of the ground-borne wave. Consequently these vibrations are most often felt when standing or sitting near the middle of such floors. In addition, any horizontal vibration of the building foundations is amplified at the upper levels of the building.

3 VIBRATION NUISANCE

Vibration nuisance often results from airborne vibration although ground-borne vibration is potentially a more severe problem under the worst combination of conditions. This is because ground-borne vibration has been found to produce the greatest motion in floors and walls and to affect the whole building whereas airborne vibration generally affects only the front rooms. The information on residents' dissatisfaction with traffic vibration was obtained from a national survey, taken in 1972, of the environmental effects of traffic and, more recently, by a questionnaire survey specifically designed to examine vibration effects and a jury experiment where the response to a range of vehicles was recorded. In this section of the report the results of these surveys are presented and discussed. Additionally, methods are given for predicting the average vibration nuisance along sections of road where airborne vibrations are dominant, and the peak vertical velocity at the foundations due to ground-borne vibration. These values can be compared with established thresholds for perception to determine if disturbance to occupants is likely to result.

3.1 NATIONAL ENVIRONMENTAL SURVEY

This large scale survey was based on a sample of 5,686 residents and was a cross-section of the adult population of England (Morton-Williams et al, 1978). It enabled vibration disturbance from traffic to be compared with the other major environmental traffic-related nuisances such as noise, fumes and dust and dirt. Figure 1 shows the percentage of respondents bothered to varying degrees by the type of disturbance. In terms of the number of people bothered it can be seen that vibration disturbance is not as prevalent as that due to noise and dust and dirt. If the percentage disturbed is plotted against traffic flow (Figure 2) it can be seen that at higher traffic levels vibration becomes relatively more disturbing compared with other nuisances. This probably results from the fact that once vibration is perceived any further increase in level of exposure rapidly becomes intrusive whereas in the case of noise there is a more gradual increase in annoyance with increasing level. This consideration will be examined further in Section 3.6 where vibration thresholds are discussed.

3.2 SURVEY OF AIRBORNE VIBRATION

This survey (Watts, 1984) was specifically designed to study the nuisance resulting from exposure to traffic vibration. The objective was to obtain information on the nature and extent of the problem and to determine the most appropriate method of predicting disturbance from physical measures such as noise and vibration. It was found that most of the disturbance was caused by airborne vibration.

3.2.1 Survey method

Approximately thirty people at each of fifty residential sites were interviewed. The sites were chosen in the south of England and the Midlands and ranged from quiet residential roads to heavily trafficked dual-carriageway. Questions on the types of vibration noticed, possible damage to property caused by vibration and the types of vehicle and the operating conditions that had produced noticeable building vibration were included. An overall rating of the vibration nuisance was obtained using a seven point scale viz:—

NOT AT ALL BOTHERED	0	1	2	3	4	5	6	EXTREMELY BOTHERED

The site median vibration nuisance ratings were determined from these scores and were used as an overall measure of annoyance at the different sites. An identical scale was used to obtain an overall rating of noise nuisance. At one house per site external noise and window vibration were recorded for 15 minutes every hour over 24 hours. At a later stage the effects of ground-borne vibration were assessed by recording vibration near the facade and in the middle of the ground floor at a small number of houses where ground-borne vibration was likely to be perceptible. The levels derived from the analysis of noise data included linear (un-weighted) levels for the frequency ranges 25–4000 Hz and 40–125 Hz,

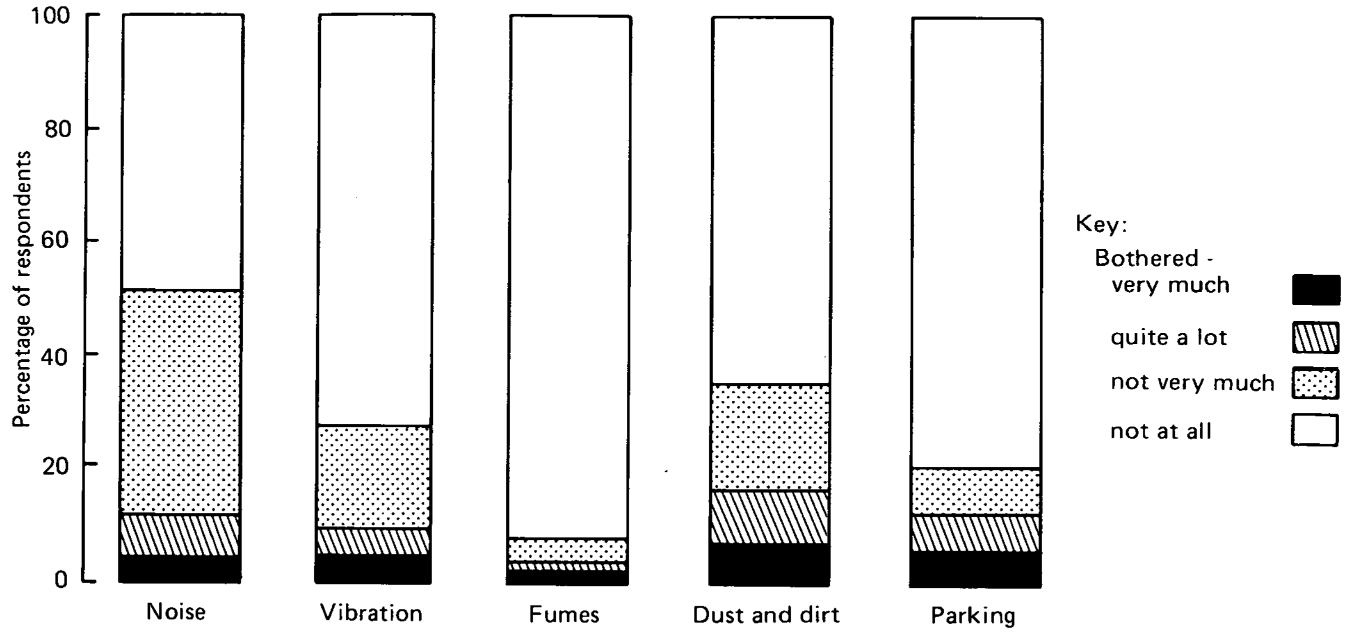


Fig.1 Percentage bothered in the home by type of disturbance caused by traffic
Source: Morton - Williams et al 1978

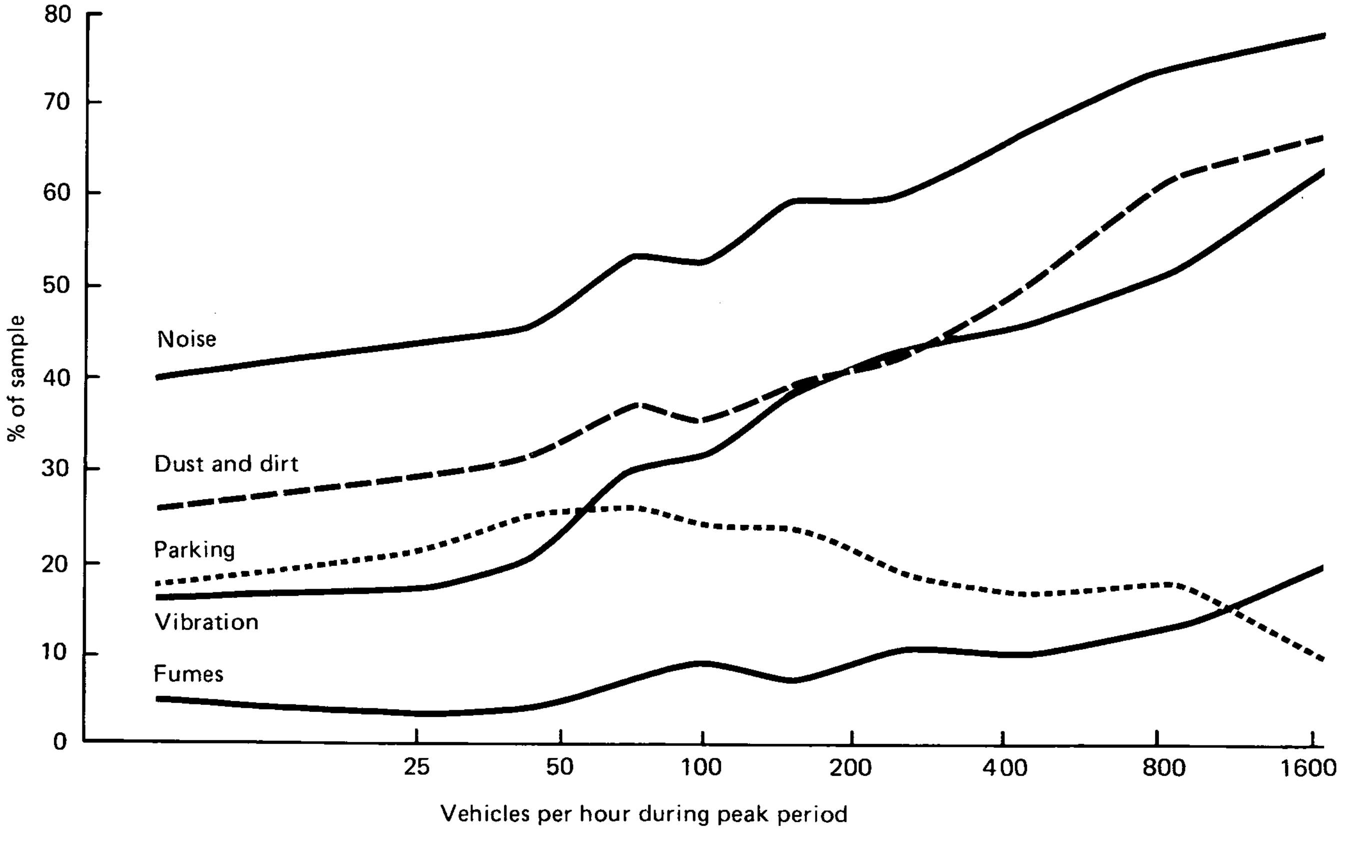


Fig.2 Percentage of respondents bothered in the home by various disturbances by traffic flow
Source: Morton - Williams et al 1978

weighted levels A, B and C and octave levels at 63 and 80 Hz.

3.2.2 Results from questionnaire survey

Results were obtained from over 1600 completed questionnaires. The percentage of respondents who noticed various traffic-induced vibrations in their homes is given Table 1. A large percentage (62 percent) noticed windows or doors rattling or buzzing and 16 percent were aware of ornaments vibrating. Vibrations were also perceived directly through tactile stimulation, for example 30 percent had noticed that the floor shook or trembled. Table 2 lists the percentage of residents who reported various types of damage thought to be caused by road traffic. Fewer people reported serious structural damage (cracks in brickwork or damaged foundations) than architectural defects such as cracks in plaster finishes. From Table 3 it can be seen that an important reason for respondents being bothered by vibration was the possibility that traffic induced vibration had damaged (20 percent) or could damage (55 percent) their homes. Large lorries were most often mentioned as causing vibration (73 percent) and buses were the next most frequently reported vehicle (51 percent).

In a further analysis (Watts, 1985a) the average percentage of residents bothered by vibration and noise at various levels of noise exposure (using the L_{10} (18-hour) dB(A) scale) was calculated (Figure 3). The large fluctuation at low exposure levels is probably due to sampling error since only a small number of sites was used to compute the percentage bothered. It was considered that a sigmoid curve was the most appropriate function to describe these data and the best fit was obtained by taking the logit transformation of the percentages and using least squares analysis. It can be seen from the figure that at a given value of L_{10} (18-hour) a higher percentage of respondents were disturbed by noise than vibration effects and this is true throughout the noise exposure range sampled. This result is in agreement with the findings of the national survey where it is likely that traffic flow was acting as a proxy for vibration exposure (see Section 3.1 and Figure 2). A similar trend of percentage bothered with noise (ie more than 'moderately annoyed') with exposure has also been reported (Fields and Hall, 1987).

3.2.3 Prediction of airborne vibration nuisance

In an attempt to determine a method of predicting the nuisance caused by airborne traffic vibration, median vibration scores were correlated with various noise, window vibration and traffic flow parameters. The median scores at each site were computed from the individual vibration nuisance

TABLE 1

Percentages of respondents who noticed various vibrations

Vibration effect	Percentage noticing effect
Windows or doors rattling or buzzing	62.2
Floors shaking or trembling	29.5
Ornaments rattling or buzzing	15.7
Traffic causing the bed to shake	13.6
Muffled sensation in the ears or fluttering sensation in the chest	18.9
Feeling vibration in the air	30.2

TABLE 2

Percentages of respondents reporting damage thought to be caused by road traffic

Damage reported	Percentage reporting damage
Roof tiles falling or moving	31.6
Cracks in plaster on walls or ceilings	25.8
Cracks in brickwork	10.0
Cracked windows	19.9
Subsidence	13.7
Damaged foundations	7.6

TABLE 3

Percentages of respondents bothered by vibration for various reasons

Reason	Percentage bothered
It has damaged this house/flat	19.6
It could damage this house/flat	54.7
It interferes with sleep	35.9
It makes you jump, or frightens you	27.0
It gets on your nerves	44.6
It feels unpleasant	41.7
It reminds you of the traffic	55.9
It interferes with the TV picture	27.3

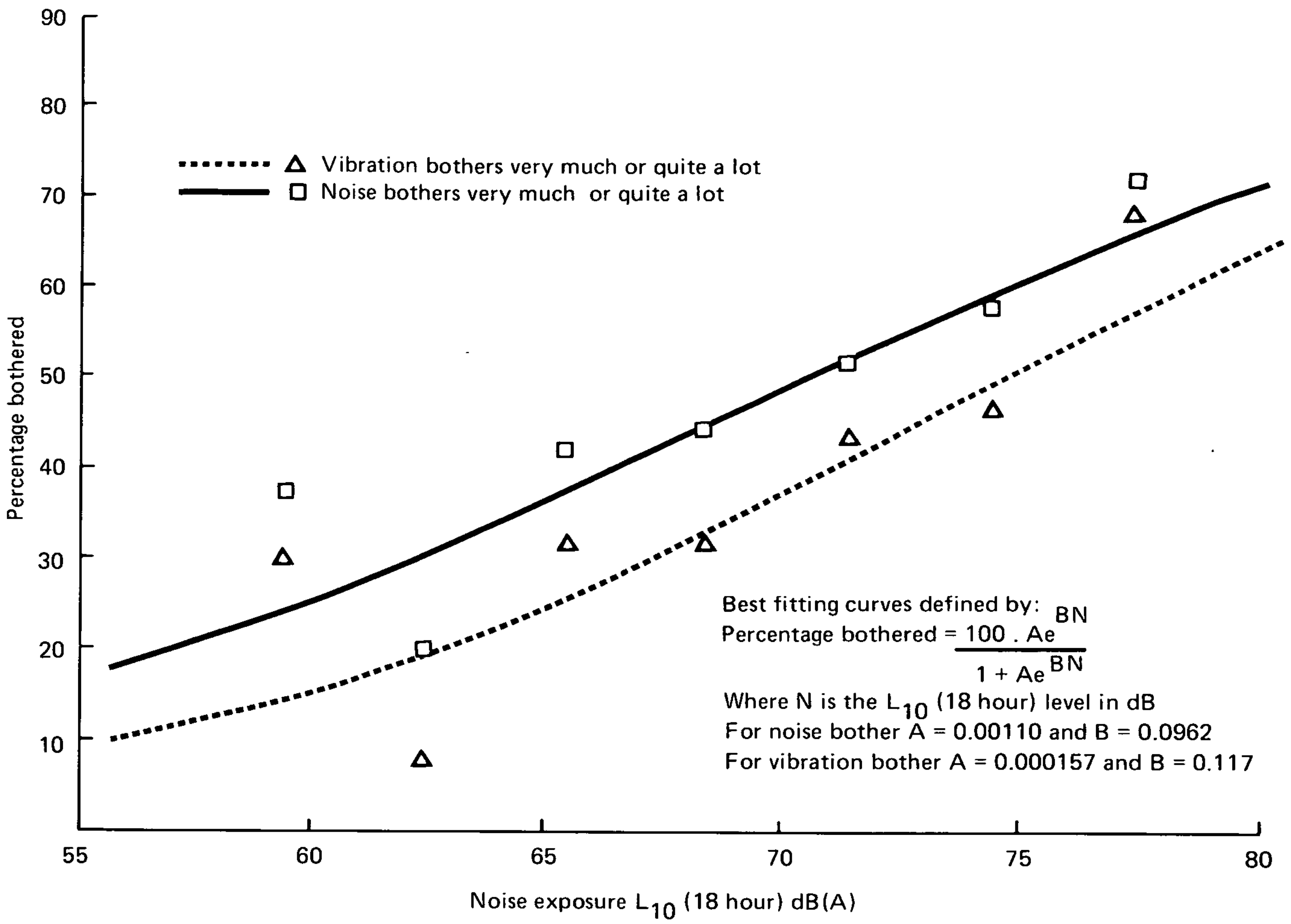


Fig.3 Percentages of respondents bothered by noise and vibration caused by traffic

ratings and therefore are an indicator of overall site nuisance. It was found that the highest correlations were obtained with the various 18-hour noise measures which are listed in Table 4. Of the measure examined, the Leq 18-hour was most closely associated with the median vibration nuisance rating ($r=0.71$). It was expected that a low frequency noise measure would be most closely related to these disturbance scores since this noise has been shown to be responsible for the common manifestations of vibrations such as window and door rattles. These noise measures were in fact marginally less well correlated than the dB(A) index, but there are no statistically significant differences between any of these correlations. Figure 4 shows a scatter plot for the L_{10} (18 hour) dB(A) index. This index is widely used for the assessment of traffic nuisance. The regression line is based on data from 49 sites, not 50, since at one quiet site adverse reactions were thought to have been caused by the recent opening of a vehicle testing station (see Watts, 1984). A reason for the small range in the sizes of the correlation coefficients in the present study is the high level of association between most of the noise measures over the 50 sites.

The results from a further study involving a group of residents who rated vibration disturbance confirmed the main result (Watts, 1985b). The jurors were seated in a living room fronting a heavily trafficked road and were asked to make nuisance ratings of selected vehicles in the traffic stream. Outside and inside noise levels were recorded and it was possible to relate noise measured on various scales to median ratings for each vibration event. As in the 50 site surveys, it was found that there was a relatively small range in the correlation coefficients for the various noise measures and that the dB(A) scale was among the most highly correlated measures.

TABLE 4

Regression coefficients relating noise exposure measures with median vibration score y as dependent variable

18-hour noise exposure measure (x)	Regression coefficients y = ax + b		Correlation coefficient	Standard error of estimate
	a	b	r	
63 Hz octave				
L_{eq}	−10.98	0.177	0.63	0.88
L_5	−10.63	0.163	0.60	0.90
L_1	−11.72	0.166	0.61	0.89
80 Hz octave				
L_{eq}	−9.86	0.164	0.61	0.90
Linear 40–125 Hz				
L_{eq}	−12.16	0.190	0.65	0.86
Linear 25–4000 Hz				
L_{eq}	−13.24	0.201	0.66	0.85
Weighted A				
L_{eq}	−10.44	0.194	0.71	0.80
L_{10}	−9.28	0.171	0.68	0.83
L_5	−10.06	0.178	0.69	0.82
L_1	−11.41	0.186	0.69	0.81
Weighted B				
L_{eq}	−11.73	0.199	0.68	0.83
Weighted C				
L_{eq}	−13.13	0.201	0.67	0.84
L_5	−13.00	0.189	0.65	0.85
L_1	−14.09	0.192	0.66	0.85
Log of number of events greater than				
90 dB (LIN)	0.274	1.363	0.69	0.82
95 dB (LIN)	1.503	1.259	0.68	0.83

3.3 SURVEY OF GROUND-BORNE VIBRATION

Results from the 50 site survey demonstrated that 18-hour noise levels at the facades of dwellings correlated reasonably well with ratings of vibration nuisance, indicating the importance of acoustically coupled vibration. However the best correlation coefficient achieved was 0.71, which implies that only 50 percent of the variance in the site median scores is explained by this measure. It was considered that a better level of association might result if measures of ground-borne vibration were included as part of the physical descriptor. Since the principal component of this source of vibration is in the vertical direction, the most likely manifestation of this type of vibration was considered to be the vertical movements of suspended floors. This would be particularly important where the forcing frequency of the vibration was close to the natural frequency of the floor since relatively high amplitudes could then occur. If these vibrations were above the threshold of perception then this could lead to disturbance in addition to any annoyance due to acoustic excitation and may result in higher than expected ratings. Perceptible ground-borne vibrations would be expected in dwellings situated a few metres from roads with uneven road surfaces and carrying HGVs. Further investigations of the road surface profile were therefore made at the survey sites to explore this possibility (Watts, 1987).

3.3.1 Method

At each of the 50 sites the TRRL Bump-integrator (Jordan and Young, 1980) was used to obtain an averaged measure of surface unevenness. This instrument consists of a single-wheeled trailer which is towed along the road at a constant speed of 32 km/hr. When in operation, the downward movement of the wheel relative to the chassis is measured and integrated. The unevenness index

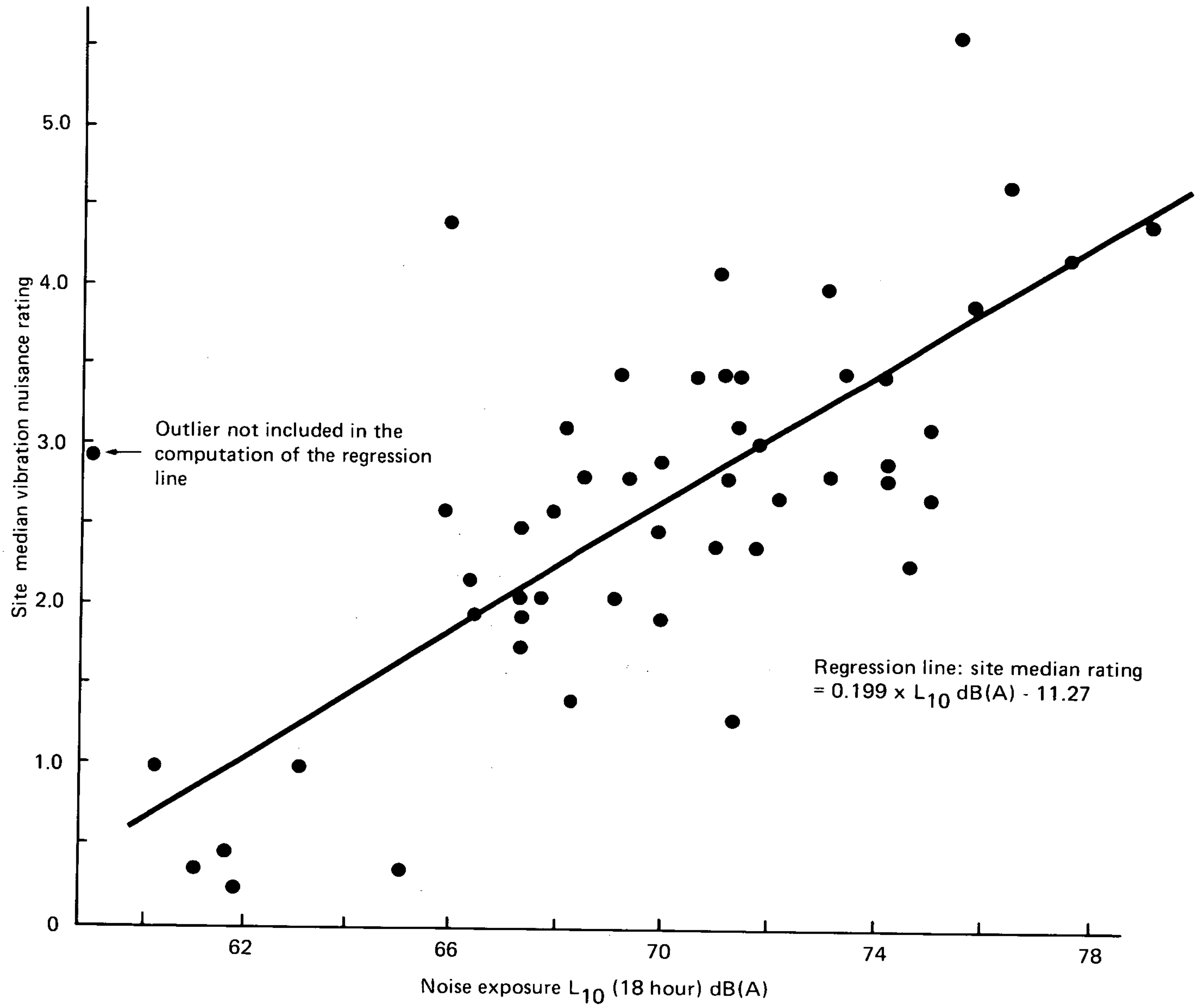


Fig.4 Median vibration nuisance rating and L_{10} (18 hour) dB(A)

'r' is computed by dividing the integrated vertical movement by the distance travelled. As before, the site median vibration nuisance score was used as the dependent variable in the regression analyses. It was expected that the contribution to the nuisance produced by the road surface would be primarily a function of the number of HGVs, the distance of the house facades from the nearside kerb (d), the unevenness index (r) and the speed of vehicles on the road (Rudder, 1978). Other parameters such as soil properties and the response of the road structure to the dynamic loads produced by vehicles were also expected to be influential but these factors could not be readily determined at this stage and they were therefore not included. Stepwise multiple regression was performed using the SPSS suite of programs (Nie et al., 1975). In this method the independent variables are entered one at a time. The variable that explains the greatest amount of variance unexplained by the variables already in the equation enters the equation at each step. In this way an optimal prediction equation was developed with as few terms as possible.

It was found that generally higher correlations were obtained by taking logarithmic transforms of the explanatory variables.

3.3.2 Results

The best fitting regression coefficients at each stage of the stepwise regression are given in Table 5. Most of the variance is explained after step 2 when the number of HGVs passing the site in an 18 hour day and the distance of the facades

TABLE 5

Results of stepwise regression analysis relating annoyance caused by traffic vibration at 50 sites to various site factors

Step	Median vibration annoyance rating predicted by:–	Multiple correlation coefficient (R)
1	$0.830 \log_{10}(1+\text{No of HGVs}) + 0.918$	0.573
2	$0.926 \log_{10}(1+\text{No of HGVs}) - 2.17 \log_{10}d + 2.69$	0.727
3	$1.10 \log_{10}(1+\text{No of HGVs}) - 1.86 \log_{10}d + 2.16 \log_{10}r - 2.88$	0.757
4	$0.845 \log_{10}(1+\text{No of HGVs}) - 2.28 \log_{10}d + 2.30 \log_{10}r + 3.41^{*} \log_{10}(\text{speed limit}) - 7.64$	0.774

Independent variables:
(No of HGVs) is the number of heavy goods vehicles with three or more axles passing the site in an 18 hour day.
'd' is the distance from the facade to the nearside kerb.
'r' is the unevenness coefficient.
'Speed limit' is limit prevailing at site.
* Regression coefficient significant at 5 per cent level.

from the kerb are included in the equation. Adding the surface unevenness term only accounts for a further 4.6 percent of the variance of the scores and the coefficient is only just statistically significant at the 5 percent level. The speed term (the logarithm of the speed limit at the site) is not significant and only accounts for a further 2.5 percent of the variance. Further measurements of vibration near the house foundations revealed that ground-borne vibrations were only likely to be perceptible at a relatively small number of houses which were close to significant surface irregularities. This explains the observation that the measure of road roughness, which is averaged over a length of road of the order of a 100 m long at each site, does not contribute substantially to the variation in median disturbance scores between sites.

The peak accelerations recorded near foundation level at dwellings where vibrations were well above perception level are given in Table 6. The data listed refer to four dwellings in Swindon and one dwelling in the London Borough of Brent.

The dominant frequencies were generally low, and they are typical of ground-borne vibration. At these sites, ground-borne, rather than airborne, vibration produced the highest peak levels of vibration in the hard structure of buildings and consequently probably had the greatest potential to cause structural damage.

TABLE 6

Peak accelerations measured at sites with perceptible vibration

Site	Vehicle producing vibration	Position	Peak vertical acceleration level (mms^{-2})	Dominant frequency (Hz)
Swindon A	5 axle artic	Foundation*	75	12
		Floor**	175	12/74
B	2 axle rigid	Foundation	130	12.7
		Floor	164	12.5
C	3 axle cement mixer	Foundation	110	13
		Floor	114	12.5
D	4 axle rigid	Foundation	42	60
		Floor	78	25.5
London Borough of Brent	Double decker bus	Foundation	57	10
		Floor	96	24

* On ground within 0.5 m of foundations.
** Middle of ground floor at front of house.

3.4 PREDICTION OF GROUND-BORNE VIBRATION LEVELS

Although ground-borne vibration problems are not likely to be as widespread as those produced by airborne vibration, maximum amplitudes can reach relatively high levels, well above the level of perception in unfavourable circumstances, and could cause anxieties about property damage. Vigorous complaints might therefore be expected under the worst combination of conditions. Ground-borne vibration effects are much more difficult to predict than those due to airborne vibration which can be simply estimated from an acoustic measure such as L_{10} (18-hour) dB(A) (see Section 3.2.3). Ground vibrations are dependent upon a number of factors which include vehicle characteristics such as axle load, suspension design and operating speed, the road surface profile and the nature of the ground between the road base and the building foundations. The response of the building to the vibrations occurring in the ground near the foundations adds a further degree of complexity to the problem.

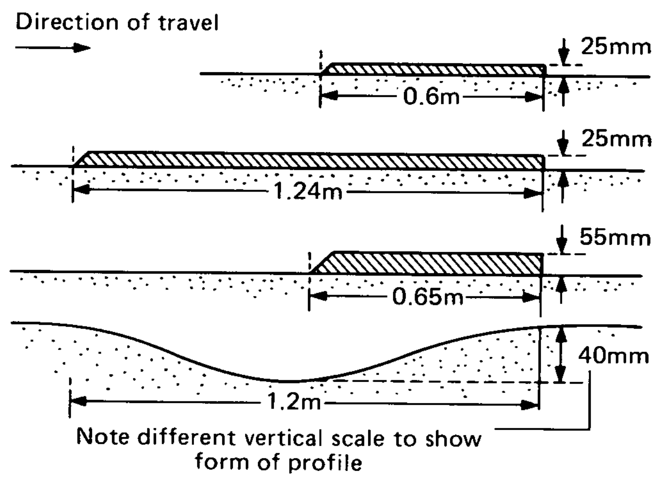
Despite the obvious difficulties of determining a practical prediction method, a relatively simple prediction technique has been developed which enables peak vertical vibration levels at the foundations of buildings to be determined. Track tests at TRRL with a wide range of HGVs established the trends in peak vibration levels with vehicle speed, load and size of irregularity (Watts, 1988a). These results were then generalized to different site conditions by determining the amplitudes and attenuation rates of vibration generated in different soils using a controlled impact method. By determining the average effects of these factors it was possible to estimate the likely range of the maximum amplitude (or peak) of vertical particle velocity (PPV) at the foundations of buildings for a variety of site conditions.

It should be noted that occasionally joints in concrete roads can give rise to perceptible vibrations due to slab movement as heavy vehicles pass by. Investigations of this effect are described in Watts (1987). There are obvious difficulties in attempting to model the generation of vibrations in these situations and consequently predictions that are developed below are for the much more common situation where a significant irregularity in the road surface is the cause of vibration effects.

The following parts of this Section review the development of this technique but a fuller description can be found in a paper by Watts (1989a).

3.4.1 Tests with HGVs

Eight HGVs, comprising rigid and articulated vehicles, were tested by running the vehicles over artificial humps and a depression on the TRRL research track. The suspension systems for the trailers covered a wide range and included two and three axle bogies with steel and air suspension and a two axle rubber sprung system. The vehicles were tested at speeds up to 80 km/h fully laden and empty over a range of profiles. These were designed to represent a wide variety of surface defects resulting from poorly backfilled holes and trenches on public roads. Figure 5 gives details of these profiles. The particle velocities produced on the track surface by ground vibrations were measured by triaxial geophone arrays fixed at 2 metres and 6 metres from the nearside wheel paths.



Note: Except for these test irregularities, the track had a level surface to within ± 7mm within 5m of the mid profile position

Fig.5 Test profiles

3.4.2 Propagation tests in different soils.

Previous measurements had indicated that traffic vibrations generated in soft ground such as alluvium and peat soils were much greater than was the case for firmer soils under broadly similar conditions (Watts, 1988b). It was therefore essential to make corrections for ground conditions when extrapolating from results obtained on the research track where the subgrade is firm sand and gravel deposits. This was achieved by measuring the transfer function between a suitable force input to the road and the resulting ground vibration for representative soil types ranging from very soft to very firm. Once determined, these functions would allow PPVs to be calculated for a particular site by factoring the PPV expected on the research track by the ratio $|H_s(f)|/|H_t(f)|$, where $|H_s(f)|$ and $|H_t(f)|$ are the moduli of the transfer function or mobilities at the site and on the track and 'f' is the forcing frequency. This frequency is typically between 10–12 Hz and results from the 'wheel hop' mode of vibration of the HGV suspension (ie the oscillatory motion of the wheels between the vehicle body and road surface).

To determine the transfer functions, the Falling Weight Deflectometer (FWD), which was designed to measure road pavement characteristics, (Sorensen and Mayven, 1982), was used to produce very carefully controlled road surface impacts. The FWD's electronics were adapted to enable the recording of the time histories of the dynamic force at the road surface and the resulting ground vibration from the impact of the falling weight. Measurements were made at 13 sites on a range of soils from very soft (peat) to hard (chalk rock). Triaxial geophone arrays were placed just beneath the surface of the ground at distances of 3, 6, 12, 25 and 50 metres from the FWD where possible. The expected values of PPV at building foundations were obtained from measurements in unloaded soils by applying a suitable factor which was obtained from comparing results obtained on buildings with those expected in the same ground at similar distances.

3.4.3 Results

Figure 6 shows a plot of vertical PPV at 6m against speed for the range of fully laden HGVs running over the 0.6 m x 25 mm high profile. There is a scatter of results indicating differences in the vibration produced by the various vehicles, but the trend with speed is clearly defined. For simplicity the differences between vehicles are not included in the model and the linear regression line was used to establish the relationship with speed. Further tests were made with smaller two axle vehicles ranging from a small estate car to a tipper lorry. As expected these vehicles generally produced lower peak levels. This can be seen in Figure 7 where PPV is plotted against gross vehicle weight for the same profile and crossing speed that were used in the HGV tests. There is an obvious trend of rising PPV with increasing vehicle weight. Since the main aim was to predict the maximum likely PPV in a stream of traffic, these-smaller vehicles were not considered in the development of the prediction model.

In Figure 8 the vertical PPVs at 6 m produced by each fully laden HGV travelling over the profiles at 48 km/h are plotted against the maximum height or depth of the profile. It can be seen that this dimension of the profile is a reasonable indicator of the likely PPV despite the wide range of profile shapes employed. Linear regression analysis showed that the average PPV at 6 m for a 25 mm high profile was 0.7 mm/s, the slope being 0.028 mm/s per mm increase in height or depth. The trend with speed over the 25 mm high profile is linear to a good approximation (Figure 6) and

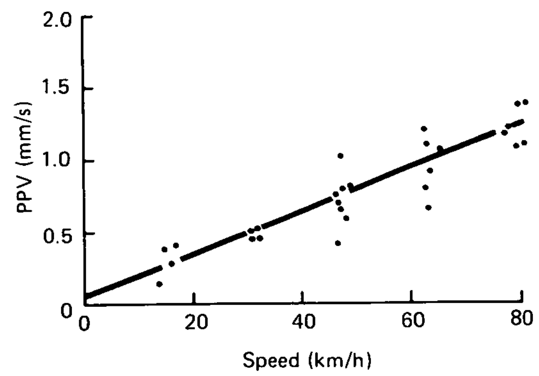


Fig.6 Vertical PPV at 6m with vehicle speed over 0.6m x 25mm hump - TRRL hump

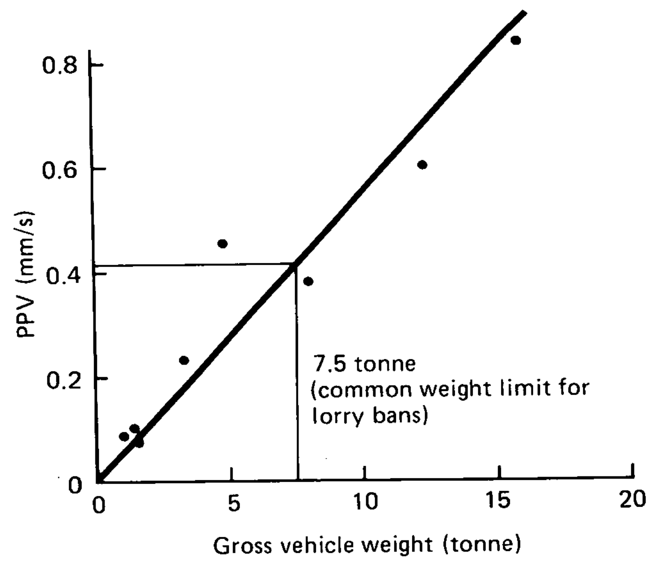


Fig.7 Variation of vertical peak particle velocity at 6m with gross vehicle weight for loaded 2 axle vehicles crossing a 0.6 x 25mm hump at 48 km/h

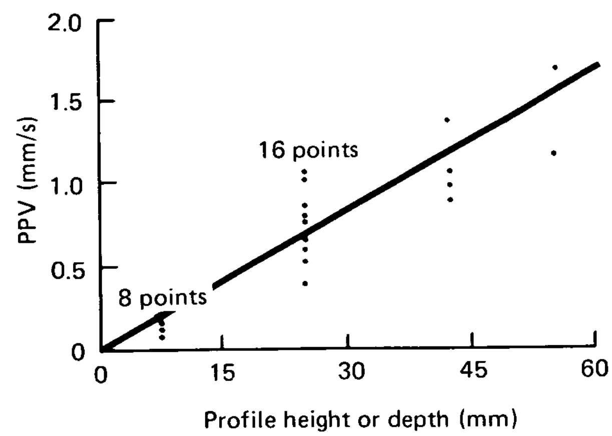


Fig.8 Vertical PPV at 6m with profile height or depth at 58 km/h - TRRL track

this was found to be the case for the other profiles. In many cases on public roads, the irregularity is significant in only one wheel path and this is usually on the nearside. Tests have shown that in this situation PPVs are generally significantly lower than the values recorded when identical profiles are in both paths. The factor 0.75 was considered appropriate for scaling predicted values in these cases.

Figure 9 shows how the moduli of the transfer functions at 12 Hz vary with distance for six different ground conditions. The Figure clearly shows that there is a large difference of up to two orders of magnitude between the response of a soft soil (peat) and very hard ground (chalk rock). Linear regression lines were fitted to the logarithmic transform of the data at 12 Hz for each site and the correlation coefficients ranged from 0.922 to 0.998, indicating good agreement with an attenuation model based on a simple power law r^x, where x is the power coefficient. Table 7 shows that there is a range of power coefficients even for similar soil types. This table also gives the average moduli of the transfer function at 6 m for six ground conditions, together with the corresponding values expected at building foundations.

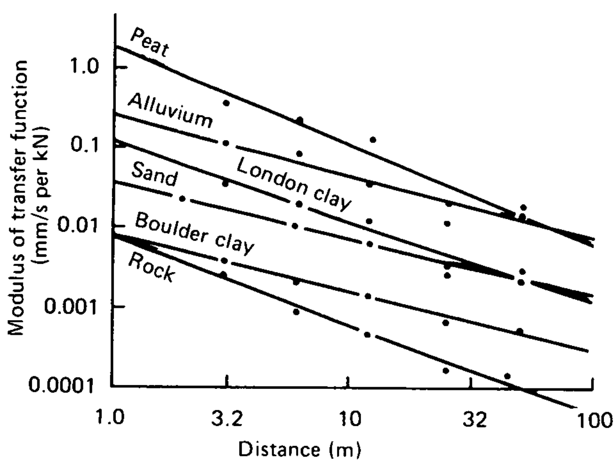


Fig.9 Transfer function for vertical PPV at 12 Hz by distance

3.4.4 Predictive model

The method is based on making predictions of vertical PPV at 6 m using the observed trends with amplitude of road surface irregularity and speed, and the most appropriate ground scaling factor. By combining these factors the expected value of maximum vertical PPV at a building foundation can be calculated as:—

$$0.028.a.(v/48).t.p.(r/6)^x$$

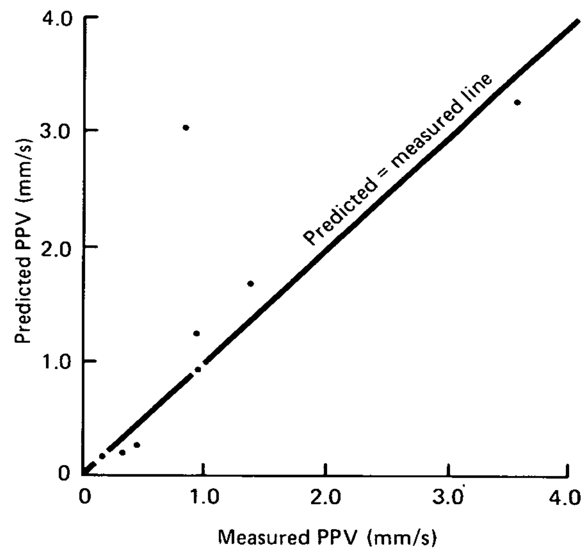


Fig.10 Measured and predicted maximum vertical PPVs at building foundations due to HGVs passing over road surface irregularities

Where a = maximum height or depth of the surface defect in mm, v = maximum expected speed of HGVs in km/h and t = ground scaling factor (see Table 7). If the surface defect occurs in one wheel path only then p = 0.75, otherwise p = 1, r is the distance of the foundation from the defect in metres and x = power factor, which can be obtained from Table 7 for the most appropriate soil type.

To check the accuracy of the formula, predictions were made at a number of sites where long-term measurements of vibration had been made. Figure 10 compares actual and predicted results, indicating that predicted results for the maximum vertical PPV are generally in reasonable agreement with the measurements.

The outlier is for a site thought to be on soft alluvium although the measured value suggests a ground scaling factor for a firmer soil would be more appropriate.

This prediction method should be useful initially in determining whether there is likely to be a ground vibration problem arising from road surface defects and the possible scale of the effects. Little is known about the subjective response to ground-borne vibration from traffic and so it is necessary in the first instance to consider whether these vibrations are likely to be perceptible. If the maximum PPV at foundation level is significantly in excess of the threshold of perception then disturbance to occupiers and even complaints may be expected. The threshold of perception is discussed in Section 3.6, but is of the order of 0.3 mm/s.

TABLE 7

Effect of ground characteristics on transmission of vibration

Ground type		Number of sites tested	Power coefficient for attenuation with distance 'x'**		Modulus of transfer function ($\times 10^3$) in mm/s per kN			Ground*** scaling factor $t = \frac{\lvert H_s \rvert}{\lvert H_t \rvert}$
					In ground at 6 m		Expected value at foundations 6 m	
Description	Condition (if known)		Range	Average	Range	Average		
Peat*	Soft	1	—	−1.19	—	189	41.9	3.84
Alluvium	Soft	2	−0.79 to −0.80	−0.79	72.5 to 82.0	77.3	77.3	7.07
London clay		3	−0.99 to −1.13	−1.06	20.9 to 56.3	33.8	33.8	3.10
Sand/gravel		3	−0.69 to −0.82	−0.74	9.92 to 11.0	10.3	10.3	0.94
Boulder clay		3	−0.71 to −1.18	−0.93	2.43 to 6.67	4.73	4.73	0.43
Chalk rock		1	—	−1.08	—	1.14	1.14	0.10

* For peat soil transfer function values and power coefficient are for 10 Hz.

** Power law for attenuation with distance is r^x where r is distance from source.

*** $\lvert H_s \rvert$ and $\lvert H_t \rvert$ are the moduli of the site and track transfer functions.

3.5 EFFECTS ON SENSITIVE EQUIPMENT AND TASKS

A further type of nuisance can arise when sensitive equipment is affected by traffic vibration (Wooton, 1975). Such problems are usually concerned with specialist buildings such as laboratories or workshops. For example there have been claims with regard to computer installations, a hydraulics laboratory (where vibration could effect the water surfaces of the large model estuaries), a machine tool laboratory and instrument workshop. Disturbance to equipment can also occur in school and university laboratories (Whiffin and Leonard, 1971) where difficulty can be experienced in reading sensitive galvanometers and operating chemical balances and various types of high magnification microscope. The vibration effects due to people using the building are sometimes overcome by mounting such equipment on slabs or frames attached to solid walls or concrete pillars. However, this does not prevent the equipment from being affected by ground-borne traffic vibration since these vibrations enter the building through the foundations and propagate readily through the hard structure of the building.

3.5.1 Effects on equipment

Information has been collected on the vibration levels which impair the operation of various types of laboratory measuring equipment (Ferahian and Ward, 1970; Instrument Society of America, 1975; Whiffin and Leonard, 1971). It appears that the satisfactory operation of electron microscopes is particularly dependent on low frequency vibration levels. For example one manufacturer has specified a PPV of 0.46 mm/s in the region 10–15 Hz corresponding to the principle frequencies of ground-borne traffic vibration, while another has set the maximum permissible level as low as 0.04 mm/s. More recently Holmberg et al. (1983) have reported a pilot survey among computer manufacturers which was designed to establish threshold values of vibration above which equipment may malfunction. Disk storage units are considered the most vibration sensitive devices in computer systems. This is because the access heads are typically supported by a thin cushion of air only 2 μm above the rotating disk. If due to vibration the access head touches the disk a failure would occur which could damage the disk resulting in expensive replacements and loss of stored data. Unfortunately threshold values given by manufacturers were defined in different ways and seldom were the measurement positions specified. The results indicated that threshold values for computer systems ranged from 0.9 to 46 mm/s for the PPV of continuous vibration at 12 Hz. The authors considered these values too low and could probably be increased.

3.5.2 Task interference

The efficiency of personnel carrying out delicate tasks requiring a high degree of skill may also be affected by the presence of vibration at the work place. The vibration may interfere directly with the task itself or may produce an annoying distraction. The British Standards Institution provides information on peak velocities in buildings below which comments or complaints are rare (BSI, 1984). For critical working areas such as hospital operating theatres and some precision laboratories the guide value for vertical peak amplitude is in the region of the threshold for perception of about 0.3 mm/s.

3.6 DISCUSSION OF VIBRATION NUISANCE STUDIES

Methods for the prediction of the average nuisance and the percentage of residents likely to be disturbed by traffic vibration at sites where airborne vibration predominates have been described. Both the vibration survey and jury experiment show that the median vibration nuisance score can be predicted by a number of different acoustic measures. This is likely to result from the fact that many of the different measures of noise levels are themselves highly correlated with each other. Therefore, although the dB(A) weighting attenuates the contributions from low frequencies (eg the 63 Hz third octave level is attenuated by nearly 30 dB) it can still act as a proxy for the low frequency sound which is likely to largely condition residents' judgements of vibration nuisance. For example, the low frequency linear noise level Leq (40–125 Hz) was well associated with L_{10} dB(A) in the survey ($r=0.91$). Consequently, for ease of prediction the L_{10} dB(A) index may be preferred since it is widely used and can itself be predicted from traffic parameters, road surface texture and site geometry (Department of Transport and Welsh Office, 1988). Section 3.3.2 shows that median vibration nuisance can also be predicted with similar precision by a composite measure based on the 18 hour HGV traffic flow and the distance from the front facade to the carriageway.

The suitability of these prediction methods in a range of circumstances must be considered if they are to be widely used in environmental assessment. The results of the survey were obtained from a study of 50 residential sites. In all cases the sites had simple geometries in that there were no intervening barriers to noise propagation such as other buildings, screening barriers, or natural features such as large earth mounds. Therefore extrapolation of the results to more complex situations should be carried out with the possible limitations clearly in mind. Consequently, where low frequency sound is attenuated by barriers of various types, predictions based on the equation developed in Section 3.3.2 involving simply lorry flow and distance from road to dwelling may overpredict the likely disturbance since no account is taken of screening effects. Predictions of annoyance based on dB(A) levels which in turn have been predicted using the Department's calculation method which take screening effects into account (Department of Transport and Welsh Office, 1988) may lead to underprediction since low frequencies may be attenuated by a smaller amount than higher frequencies (Hothersall et al., 1989). For these reasons, predictions for these more complex situations should be made cautiously. Greater confidence can be placed on predictions where the site geometries lie within the range of variables covered in the survey.

Section 3.4.4 describes a method for making predictions to determine whether ground-borne vibrations are likely to be above an established threshold of perception at foundation level. However, it is necessary to determine if a particular threshold is applicable to traffic vibration and the level at which the vibrations might be expected to become unacceptable. Early studies by Reiher and Meister demonstrated that for sinusoidal vibration the threshold of perception in the vertical direction was 0.3 mm/s (Steffens, 1974) and, recently, similar results have been obtained for frequencies near the wheel-hop frequency (Parsons and Griffin, 1988). In the latter study the effects of short duration sinusoidal vibration were examined and this is particularly relevant since the time histories of ground-borne vibration from HGVs travelling over a surface defect often reveal just one or two major peaks per axle. The threshold for these short duration events of one or two major cycles was 1.7 times the value for continuous vibration at the same frequency (16 Hz). In a further test, subjects were asked to adjust the vibration level until they considered it would be just unacceptable if it occurred in their own home. It was tentatively concluded that vibration may become unacceptable when the threshold is exceeded by a factor of two, and consequently it appears that vibrations due to ground-borne traffic vibration may become unacceptable above a level of 1 mm/s. It should be noted that this value was derived from the average response of a relatively small sample of subjects. Clearly there will be some residents who are more sensitive to vibration effects and who will find lower levels unacceptable.

A further consideration is the extent to which vibration levels at the foundations relate to levels on living room and bedroom floors. A number of studies have shown that ground-borne vibration levels on ground floors are similar to those at the foundations but that amplification often occurs at higher levels in buildings (Watts, 1987; Watts, 1988c; Watts, 1989b). For example, it is possible that peak vertical particle velocities in the middle of upper floors may be several times that at the foundations. Potentially this could lead to greater annoyance, although a person lying down, for example, may not be exposed to these higher levels because of the attenuation afforded by the mattress and springs of the bed. On the available evidence it is not possible to give precise guidance on the level at the foundations above which complaints from occupants can be expected. However if the levels are significantly above 0.3 mm/s then some degree of disturbance will probably occur while if levels are well in excess of 1.0 mm/s then this may prove unacceptable and complaints may be made.

It appears that under unfavourable conditions traffic vibrations have the potential to degrade the performance of sensitive equipment and interfere with delicate tasks. It is difficult to give general guidance on the levels of vibration and their frequencies which will produce these effects since the response of a particular system will depend not only on design details but may also be determined by the mounting conditions. For example, the problem can occur because lightly damped, finely balanced, movements in some precision measuring equipment exhibit sharp resonance peaks when excited at certain frequencies. A small change in the design details may shift the resonant frequency outside the range of ground-borne vibration and, as a consequence, the detrimental effects may not be observed. For this reason the effects of vibration are likely to vary greatly even for equipment of a similar type. In some cases equipment manufacturers may provide sufficient details about vibration sensitivity to allow the likely impact of traffic vibration to be reasonably assessed. In cases of doubt it may be necessary to expose the equipment and operator to a range of frequencies typical of that produced by traffic vibration, and establish the vibration levels which produce a detrimental effect. These levels can then be compared with levels expected from traffic at the particular location.

4 VIBRATION DAMAGE

There is concern about the effects of traffic vibration on buildings close to heavily trafficked roads. The survey of vibration nuisance described in Section 3.2 has shown that over half the respondents were bothered by traffic vibration because they felt that traffic vibration could damage their homes; nearly 20 per cent alleged vibration damage had already occurred. In addition the Civic Trust, consulting engineers and academics who are involved in the preservation of historic buildings and monuments have expressed concern at the effects of traffic vibration on these sensitive buildings (Civic Trust, 1970; Crockett, 1966 and 1973; Bata, 1971). Increases in allowable vehicle weights may have heightened concerns and anxieties (Armitage, 1980). Despite these concerns there was little evidence to support or reject these beliefs and it was necessary to study the problem using a variety of techniques and involving a wide range of buildings and soil types so generalizations could be made with some degree of confidence.

4.1 POSSIBLE DAMAGE MECHANISMS

There are four mechanisms that may result in vibration damage in buildings. Three can affect the structure directly and the fourth may act indirectly by modifying the underlying soil which in turn may affect the structure.

4.1.1 Direct effects

If vibration levels are high enough the stresses imposed by shear and compressional waves can cause failure of building components. Much work has been carried out by the USA Bureau of Mines where the effects of vibration from blasting have been extensively studied. Peak particle velocity of the hard structure of the building near foundation level is the measure most frequently used since it can be related to the stresses imposed on the structure by the propagating waves (New, 1988). Studies such as these have shown no conclusive evidence of significant vibration damage below a PPV of approximately 10 mm/s (House, 1973; Nelson and Watts, 1988), whereas measurements at the foundations of buildings adjacent to heavily trafficked roads have shown PPVs up to only 3.5 mm/s (Watts, 1988b).

Although these peak levels from traffic are well below vibration levels that have been shown to produce damage, it is not inconceivable that direct damage may occur at lower levels. A small additional stress imposed by traffic vibration might possibly add to a much greater static stress resulting in damage. Such a 'trigger' mechanism could perhaps cause premature failure in a building component already weakened by other causes. A more widespread concern is the possibility of fatigue damage occurring as a result of long periods of exposure to low levels of vibration. Buildings close to heavily trafficked roads may be exposed to many thousands of stress cycles each day so that the vibration dose over many years could be considerable.

4.1.2 Indirect effects

It is known that granular soils such as sand can be induced to change volume if subjected to vibration. This phenomena has been studied under laboratory conditions (Linger, 1963) and the tendency is for the soil to densify as the particles move closer together under the action of vibration. Such assisted densification could lead to settlement and structural damage if it occurred under building foundations. The risk of serious damage would be particularly high if differential settlement occurred due to the relatively high exposure of the front foundations compared with the rear where vibration levels would be attenuated to some degree. Buildings probably at greatest risk are those constructed without proper foundations on loose or low density sands or soft soils. Such vibration assisted settlement has been suggested as a cause of tilting of the walls of churches and cathedrals towards the nearest heavily trafficked roads (Crockett, 1973).

4.2 DESIGN OF EXPERIMENTS

There are a number of difficulties in attempting to study the possible effects of traffic vibration on buildings. An important consideration is the scale of the likely effect when compared with those produced by other causes of damage. A cursory inspection of buildings adjacent to busy roads show that they are not obviously deteriorating faster than similar buildings further away. Traffic vibration in city centres is subjecting buildings to hundreds of millions of stress cycles every year without any obvious widespread damaging effects. It is therefore likely that, if they occur at all, the effects of traffic are probably relatively small, taking many years to have any measurable effect. The research method must therefore be capable of separating any small damage caused by traffic vibration from damage due to natural ageing and weathering of materials and settlement that might take place on loose or soft soils. In addition, major alterations and additions to buildings may, over several years, have a significant impact on structural integrity.

There were four types of study that were carried out in order to quantify the possible effects of vibration.

(i) A fatigue study was carried out on an unoccupied dwelling using simulated traffic vibration. This separated the effects of vibration and ageing and allowed virtually unambiguous evidence to be obtained on the isolated effects of vibration since the site conditions remained constant except for the addition of vibration. It was possible to examine the effects of both airborne and ground-borne vibration.

(ii) A pairwise comparison of occupied buildings fronting heavily trafficked roads with similar buildings in the neighbourhood but in quiet areas away from traffic was carried out at three sites. The objective was to determine if any excess damage was detectable in houses most exposed to traffic vibration.

(iii) A case by case examination of heritage buildings was carried out with the assistance of structural engineers from the Historic Buildings and Monuments Commission for England (English Heritage). Buildings showing signs of distress and exposed to relatively high levels of traffic vibration were identified and a structural survey was carried out in order to identify the probable causes of the observed damage.

(iv) A review was made of both published and unpublished studies dealing with the effects of traffic vibration on heritage buildings. In some cases an attempt was made to check the likely accuracy of the original data and the conclusions that had been drawn.

4.3 FATIGUE STUDY

This study, which was conducted under contract by Travers Morgan Planning, involved the exposure of a conventional two storey building to simulated traffic vibration. The intention was to expose the house to the equivalent of many years of heavy traffic using simulated sources of airborne and ground-borne vibration. Throughout the exposure period the building was carefully monitored to determine the precise nature of any damage or settlement. A full description of the study can be found in Hood and Marshall (1987) and Watts (1988c).

4.3.1 Site description

The test building was a recently vacated pair of semi-detached houses built on medium density sands. The sand was loose down to a depth of approximately 1.5 m and below this level it was lightly cemented. The houses were built at the beginning of the century and were constructed of brickwork in lime mortar. Test foundation strips were also constructed so the effects of ground-borne vibration on foundations under different static loads could be investigated. The general layout of the site is shown in Figure 11.

4.3.2 Simulation of vibration

Airborne traffic vibration was simulated using four large loudspeakers mounted in the wall of a high sided refrigerated lorry parked adjacent to the house facade (Figure 11). A computer was used to generate a low frequency waveform which when suitably amplified produced a peak linear sound level of 110 dB at the facade. Initially the system was used to generate a broad band noise characteristic of heavy goods vehicles but the resulting vibration was lower than expected. In order to create higher vibration levels the frequency was adjusted to produce resonance in the window adjacent to the loudspeaker system.

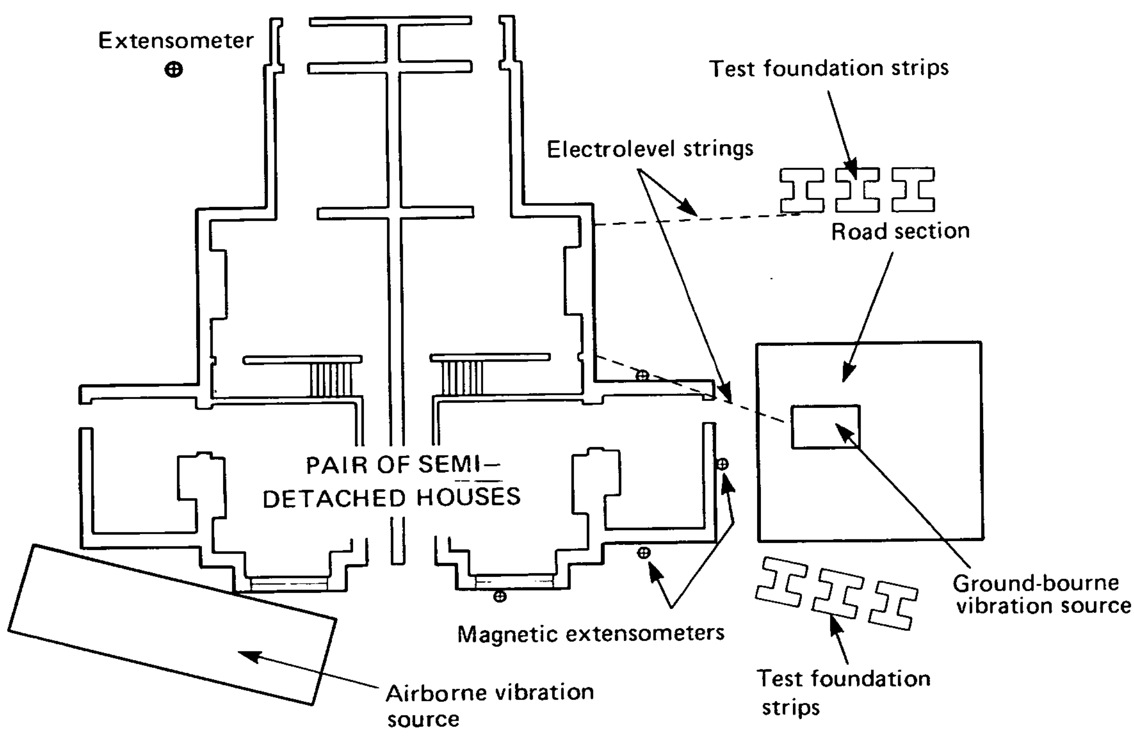


Fig.11 Site layout for fatigue test of a pair of semi-detached houses

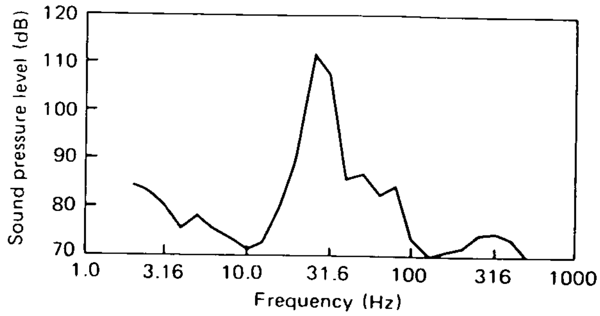


Fig.12 Third octave sound levels in gap between speaker array and facade - house fatigue test

Figure 12 shows that the principal frequencies of the simulated sound lay in the 25 Hz third octave band. By carrying out this adjustment the generated vibration levels were at or above the highest levels likely to be produced by vehicles passing close to a building. During the experiment it was estimated that the simulation produced an exposure to noise equivalent to the passage of approximately 500 000 HGVs.

Ground-borne traffic vibration was simulated using a geophysical vibrator located 2 m from a side wall of the building (Figure 11). Levels were adjusted so that the vertical PPV at foundation level adjacent to the vibrator was in the range 2.5–3.0 mm/s. This is close to the extreme end of the range of peak velocities that have been recorded in buildings close to significant road surface irregularities during the passage of heavy vehicles (see Section 3.4.4). The frequency was adjusted to approximately 13 Hz, which is within the range of frequencies produced by HGVs, and this input produced a relatively large response in the structure. Figure 13(a) and (b) show the time

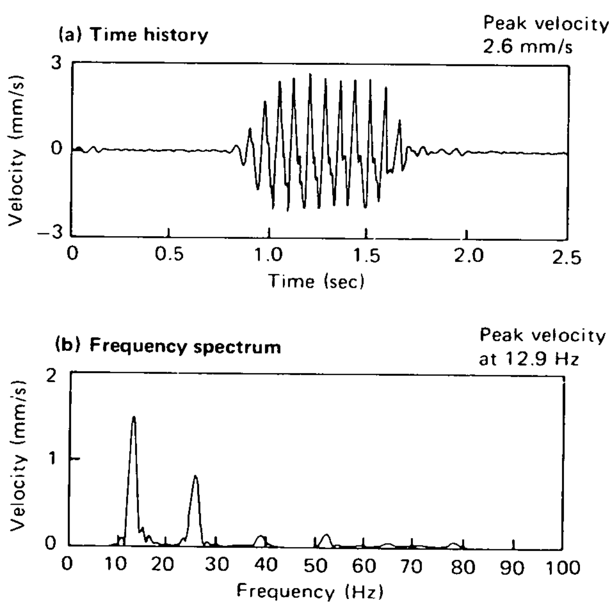


Fig.13 Vertical particle velocity at foundations adjacent to vibrator - house fatigue test

history and frequency content of a typical pulse. The house was exposed to 880 000 such pulses which was estimated to have simulated the effect of over 3.5 million HGVs axles passing over a large surface irregularity near the house.

4.3.3 Monitoring techniques

During the exposure period, which lasted approximately three months, the building and surrounding soils were carefully monitored using instruments capable of resolving movements of the order of 0.1 mm/s. Electrolevels and extensometers were employed to measure soil movements and levelling stations were installed at 36 locations on the structure to determine any foundation settlement. In addition, high resolution Moire photography was used to indicate if differential movement of the building facade had occurred.[1] Forty existing cracks in various locations were monitored for movement with a Demec gauge. At various stages throughout the experiment an inspection of the building was made and any further cracking was recorded. Vibration measurements were also made throughout the house so the response of the house could be determined and damage mechanisms identified.

4.3.4 Results

The whole building responded relatively strongly to ground-borne vibration and generally the highest levels were recorded in suspended wooden floors and ceilings on the first floor. These vibrations were very noticeable and would have been unacceptable to most occupants. Acoustically induced vibrations were only perceptible in rooms close to the noise source and were generally below those produced by the vibrator despite the high levels of low frequency noise produced by the simulator. It was concluded that the exposure to airborne vibration did not produce any observable damage.

Ground-borne vibration produced no detectable settlement of the house. The accuracy of the levels were +/−0.3 mm. It was anticipated that the sands under the foundations would densify under the action of vibration since the measured in situ density indicated a potential settlement of up to 20 mm was possible. Tests on the soil after the exposure period revealed that it was likely that no densification had occurred and it was concluded that the vibration levels being generated were insufficient to compact this particular soil further. Moire photography showed that, apart from one small area close to the vibrator, there was no differential movement within the house facade at

[1] The front facade of the building was covered with paper on which was printed rows of dots. Movements of the house would produce Moire fringes between pairs of photographs of the papered walls.

any time during the experiment. The amount of movement detected in the one area where it was observable was only 0.4 mm which is just significant since measurement error using this technique was estimated to be +/−0.2 mm.

No structural or trigger damage was found but fatigue damage occured in some plaster finishes. The most significant cracking occurred in the end wall of the house facing the vibrator and in ceilings close to the chimneys. The amount of damage was very slight and probably would have gone unnoticed in a normally decorated house. The absence of trigger damage may have been due to the extensive cracking in the plaster which existed prior to exposure. Many of these cracks were very large and some allowed movements within the plaster in response to the vibration (Watts, 1988d) which may have prevented damaging stress concentrations. Of the 40 cracks which were monitored for movement, only five showed significant changes of 0.1 mm or more during the exposure period.

Settlements of between 1 and 14 mm occurred in the test foundation strips. This was not due to densification of the underlying soil but was caused by a migration of soil particles which resulted in a small amount of rotation of the strips. It was considered that rotation of a facade of the main building might have occurred if it had been poorly tied to the rest of the structure. In addition, settlement might have taken place if the layer of loose sand under the foundations had been deeper. It is also possible that settlement might have occurred if the soil type had been different eg saturated sand, soft clay or peat. During the experiment none of these effects did in fact occur.

4.4 PAIRWISE COMPARISONS

The objective of this study was to determine if excess damage occurs in occupied houses which have been exposed to relatively high levels of traffic vibration over a considerable period of time when compared with similar houses that have not been exposed to significant vibration. A full description of the study, which was carried out under contract by Travers Morgan Planning, can be found in Muskett and Hood (1989).

4.4.1 Description of sites

Worst case conditions were sought so that the effects of these vibrations might more readily be detected. Since differential settlement did not occur on sands in the simulation test described above, it was considered worthwhile to investigate the possibility of this effect occurring in soft ground such as saturated alluvial deposits. Therefore suitable rows of houses were sought in areas where there were known to be generally soft soils. Sites were found in King's Lynn, Bridgwater and Cardiff and at each site similar rows of houses built on comparable soils but exposed to very different levels of vibration were identified.

Table 8 lists the number of light and heavy vehicles at each exposed site. At Saddlebow Road, in King's Lynn, the buildings were within 10 m of the main road which carried a substantial flow of heavy vehicles. The control site at Beloe Crescent is a cul de sac and levels of traffic were in consequence very much lower. The houses at both exposed and control sites form part of a council estate and originally were all of very similar design. All the houses were constructed between 1927 and 1947 and were of traditional construction being two-storey with brick load bearing walls and with mass concrete strip foundations.

The houses at the exposed site in Bridgwater (Bristol Road) were approximately 5 m from the carriageway. This road forms a major radial route into Bridgwater from the north and the flow of lorry traffic is relatively high. The traffic at the control site in Devonshire Street was very low and parked cars lined the road. The houses at both exposed and control sites were similar and they were built in terraces c1890. The houses were of traditional construction comprising brick load bearing walls.

In Cardiff the exposed buildings in Penarth Road were within 10 m of the carriageway which carried a very high volume of traffic. The control properties were in a cul de sac (Chester Place). The buildings at control and exposed sites were similar, being two-storey terraced properties in

TABLE 8

Paired comparison study—traffic flow at exposed sites between 7:00–19:00 hours

Site	Direction	Light vehicles*	Heavy vehicles**	Percentage of heavy vehicles
Saddlebow Road in King's Lynn	Southbound	3 165	432	12.0
Bristol Road in Bridgwater	Southbound	6 482	901	12.2
Penarth Road in Cardiff	Eastbound	10 233	1 012	9.0

* Light vehicles—cars and goods vehicles <1.5 tonnes.
** Heavy vehicles—goods vehicles >1.5 tonnes, buses and coaches.

TABLE 9

Paired comparison study—peak vertical particle velocity at foundations and L_{10} linear noise level

Site		Peak vertical velocity (mm/s)	L_{10}* linear level (dB)
King's Lynn	Saddlebow Road (exposed)	0.96	87.5
	Beloe Crescent (control)	<0.10	83.5
Bridgwater	Bristol Road (exposed)	1.16	89.5
	Devonshire Street (control)	<0.08	77.6
Cardiff	Penarth Road (exposed)	0.42	89.0
	Chester Place (control)	0.25	82.0

* L_{10} linear level is the unweighted level which is exceeded for 10 per cent of the recording period.

TABLE 10

Paired comparison study—number of houses inspected for damage

Site	Exposed row			Control row		
	External and internal	External only	Total	External and internal	External only	Total
King's Lynn	6	—	6	3	—	3
Bridgwater	6	15	21	1	12	13
Cardiff	3	7	10	4	7	11

stone or brick. It was estimated that these dwellings were built at the turn of the century.

4.4.2 Exposure to vibration and noise

Vibration measurements were made at the foundations of the properties fronting the heavily trafficked roads and also at the control sites so that the peak levels of vibration could be established and a check could be made that significant differences in exposure did exist between the two groups of houses. Noise measurements were also made at both exposed and control sites during similar times of the day so comparisons could be made. As expected, both vibration and noise exposures were very much greater at exposed sites than at control sites (see Table 9). Vibration levels at the exposed sites were all relatively high, exceeding the level of perception (0.3 mm/s) at the foundation of the buildings.

4.4.3 Comparisons of building damage

The comparisons of building damage in exposed and control properties was a difficult task requiring skilled professional judgement. Although numerical indices for damage assessment have been developed (BRE, 1966) these are normally only applicable to large scale damage involving significant cracking. A further problem when making assessments in occupied properties is that minor damage is often repaired and covered by redecoration work. More serious damage occurs more rarely but it is easier to identify especially if it involves cracking or differential settlement of external brick or stone work.

Table 10 shows the numbers of houses inspected at exposed and control sites at each of the three sites. In many cases it proved impossible to obtain permission to carry out internal inspections and so the survey relied heavily on the comparisons of external defects. To complete the surveys of damage, the vertical alignment of the front facades of houses was measured with a theodolite to check if there was evidence of excess tilting towards the major roads at exposed sites. This might possibly be expected if vibration settlement occurs since vibration levels will tend to be greater at the fronts of buildings because these facades are closer to the source of vibration.

Soil investigations were also carried out to determine reasons for any possible tilting of properties. Trial pits were dug close to selected properties at both exposed and control properties at the three sites. This allowed the soil types and shear strengths to be determined at and below foundation level.

4.4.4 Results

Results showed that at all sites there were no significant differences in the amount of damage in exposed and control properties. It is possible that some minor damage effects may not have been found because of the problems of identifying this level of damage in normally decorated and occupied homes. There were also considerable differences in the conditions of individual houses within any one group of buildings due to the variation in the level of maintenance. This added further to the difficulties in detecting any vibration effects which might possibly be present.

With the exception of King's Lynn, there were no significant differences in the degree of tilt between exposed and control properties. Analysis of the results at King's Lynn revealed that there was a statistically significant tilt towards the road at the exposed site ($p < 0.02$) but that at the control site there was no significant trend in any direction. The soil investigations revealed the presence of very soft ground at the front of a property at the exposed site and enquiries established that this was on the line of an old drainage ditch. It was further established that the ditch had been filled during construction of the houses. It was concluded that the presence of the soft ground under the foundations of the exposed facade was a probable reason for the tilt of these buildings towards the road, so it could not be ascribed to the effect of traffic vibration.

The buildings examined were typical urban terrace dwellings built on relatively soft ground near the turn of the century and were probably exposed to generally high levels of traffic vibration over many years. Although these conditions can reasonably be considered to be conducive to inducing vibration effects there was no evidence that damage had been caused by heavy traffic.

4.5 HERITAGE BUILDINGS

In order to assess the possible contribution of traffic vibration to damage in older properties, eight buildings showing signs of distress and exposed to relatively high traffic vibrations were identified and examined. Vibration, noise and crack movements were monitored and soil conditions at each site were examined and traffic flow levels recorded. English Heritage, which has responsibilities for historic buildings and monuments of national importance, collaborated in this research by carrying out structural surveys of the buildings and by providing written reports of the observations. The main objectives of this study were:—

(i) to quantify the vibration exposure and the response of the buildings.

(ii) to determine the condition of the buildings and identify damage.

(iii) to attempt to determine the main causes of any observed damage.

The study was carried out in two phases. In the first phase four brick built grade 2 listed buildings were examined (Watts, 1988b) while a much wider range of buildings in terms of age, size, and type of construction was studied in the second phase (Watts, 1989b).

4.5.1 Description of buildings

The sites were selected to represent the 'worst case' conditions (ie where it was considered that by virtue of the combination of high vibration levels, soil and building conditions, there was some potential risk of vibration damage occurring). Sites were found within a few metres of roads carrying HGV traffic and generally this was at a high level producing perceptible ground-borne vibrations at foundation level. Soil conditions included wind blown sand deposits and soft soils such as saturated peat and alluvium since it was considered that these soils had the greatest potential to cause settlement as soil particles beneath the foundations could possibly densify or migrate when vibrated.

Table 11 provides descriptions of these buildings and includes details of approximate age and significant alterations that had been made to the structure of the buildings. There was a wide range in the sizes, ages and types of construction of these buildings. The oldest, and also the largest, was the 15th century parish church in the centre of Louth in Lincolnshire. The building was over 60 m long and the spire is one of the tallest in the country. The most recent building studied was a large house originally built as an inn at the beginning of the century but which has since been converted to a farmhouse. At this site it was possible to investigate the likelihood of trigger damage since during the study the lorry traffic increased significantly over a short period of time due to the opening of a gas pipeline store within 100 m of the property. By studying the building before and after the increase in lorry traffic any new damage resulting from traffic vibration could be identified.

4.5.2 Measurement and survey methods

To determine the exposure of the buildings to vibration, peak amplitude and rms values of particle velocity and acceleration were measured at various parts of the building. Crack movements were also recorded to supplement this information. Noise measurements were made at the facades of

TABLE 11

Case studies of heritage buildings—description of buildings

Site number	Description	Number of stories	Construction	Significant alterations	Approximate age
1	Shrimpers cottage in terrace	2	Brick	None	Late 18th C
2	Detached house	2	Brick	None	Mid 19th C
3	Cottage	2/3	Brick	Ground floor converted to shop	Early 19th C
4	Large house	2	Brick	Ground floor converted to public bar	Early 18th C
5	Georgian town house	4	Stone	Ground floor converted to shop	Mid 18th C
6	Large parish church	—	Stone	Spire added in 16th C	Early 15th C
7	Cottage	2	Timber-framed with brick extension	Porch and bell cote added in 19th C Mid 20th C extension	15th C
8	Large farmhouse	2	Stone and brick	Built as an inn converted to dwelling	Early 20th C

buildings to quantify the level of low frequency noise. In addition surveys were made of the traffic and soil conditions at each site. Table 12 gives details of the site conditions including the flows of light and heavy vehicles and the peak vertical particle velocities at the most exposed foundations recorded during the day. The farmhouse (site 8) was examined before and after the large increase in lorry traffic and it can be seen that there is a corresponding increase in the peak particle velocity recorded in the after period.

Building surveys were carried out by structural engineers at the same time or shortly after measurements were made. The engineers identified damage both internally and externally and recorded defects on building plans. Recorded damage included cracks in plaster finishes, brick and stone work and distortions of walls and ceilings. Significant cracks were monitored using a Demec gauge. The structural engineers had a wide experience of common types of damage in other buildings of similar type to the ones examined in this study and this provided a useful reference when they assessed the likely effects of traffic vibration.

4.5.3 Results

It was found that ground-borne vibration generated by passing HGVs was the most significant source of vibration at all sites. However, it was demonstrated that other activities such as slamming doors, jumping on upper floors, and in the case of the church playing the organ, could produce similar or greater levels of vibration, although the frequency of such events would normally be much lower than the number of vibration events produced by traffic. Peak levels of vertical particle velocity at foundations were above the level of perception established by Reiher and Meister of 0.3 mm/s (see Section 3.6) at all sites except the farmhouse. Maximum vibration amplitudes were greater on upper floors and walls at the fronts of the buildings than at foundation level. The damage surveys identified a range of defects in the buildings ranging from cracks in plaster finishes to more substantial structural damage resulting from foundation settlement. Brief details of some of the more significant case studies are given below. In all cases it was concluded that the main causes of the damage observed was not traffic vibration.

TABLE 12

Case studies of heritage buildings—description of site conditions

Site number	Location	Soil description	Total flow between 10–19:00		Peak vertical particle velocity recorded between 10–19:00 (mm/s)
			Light*	Heavy**	
1	Botanic Road, Southport	Blown sand	4 288	349	0.92
2	Monmouth Street (A38) Bridgwater	Alluvium	11 916	1 600	0.80
3	Wisbech Road (A47) Thorney	Gravelly sand overlying peat	4 008	1 192	3.52
4	Double Street Spalding	Alluvium	2 480	548	1.37
5	Widcombe Parade (A36) Bath	Silty sand, soft clay layers beneath	8 472	980	0.92
6	Upgate (A16) Louth	Sand, gravel and Marl clay	4 572	652	0.33
7	A435 Norton	Sand, gravel and clay	5 664	1 212	0.46
8	C-road nr Honiton	Silty clay overlying soft rock	Before pipe store opened		
			372	48	0.11
			After pipe store opened		
			593	118	0.16

* Light—cars and goods vehicles < 1.5 tonnes.
** Heavy—goods vehicles ⩾ 1.5 tonnes, buses and coaches.

Shrimpers cottage in Southport, Merseyside

The side wall of this building formed one side of a waggon porch which led to the rear of the property and it was severely cracked (see Plate 1 and 2). Close to this wall ran an old sewer pipe and it was thought that the trench above may have been poorly backfilled and so caused settlement of the foundations resulting in the structural cracks. A tapered brick course near the foundations indicated that this distortion of the building had occurred many years ago, so it was not related to the effects of recent heavy traffic.

Cottage at Thorney, Cambridgeshire

This building was generally in a poor condition having very marked distortions in floors and walls. The low wall fronting the A47 was leaning towards the road and was out of plumb by 170 mm at one point (see Plate 3). This was thought to be due to a deep layer of peat under the footings shrinking over the years and causing the settlement problems. That this process had occurred was indicated by the fact that settlement had taken place in buildings in the same terrace not exposed to high levels of traffic vibration. Another reason for the poor state of the building was the fact that structural supports had been removed to provide an open plan area on the ground floor. This is likely to have weakened the structure considerably and produced over a period of time some of the distortions of brickwork and floors on upper levels in the building. It is possible that traffic vibrations had accelerated the natural process of settlement but there is no evidence that this is the case.

Parish church at Louth, Lincolnshire

There was much concern that traffic vibration was causing damage to stained glass windows at the

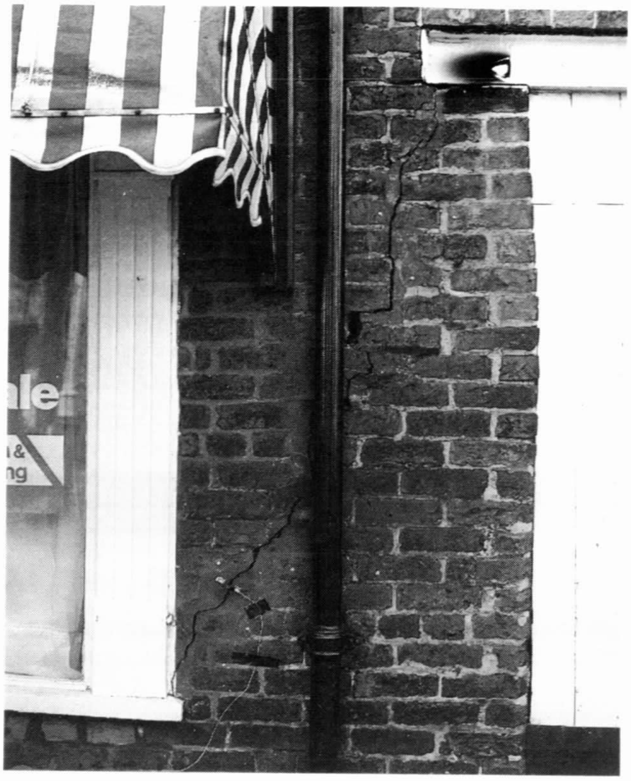


Plate 1 Entrance to Waggon Porch in Shrimpers cottage showing vertical crack

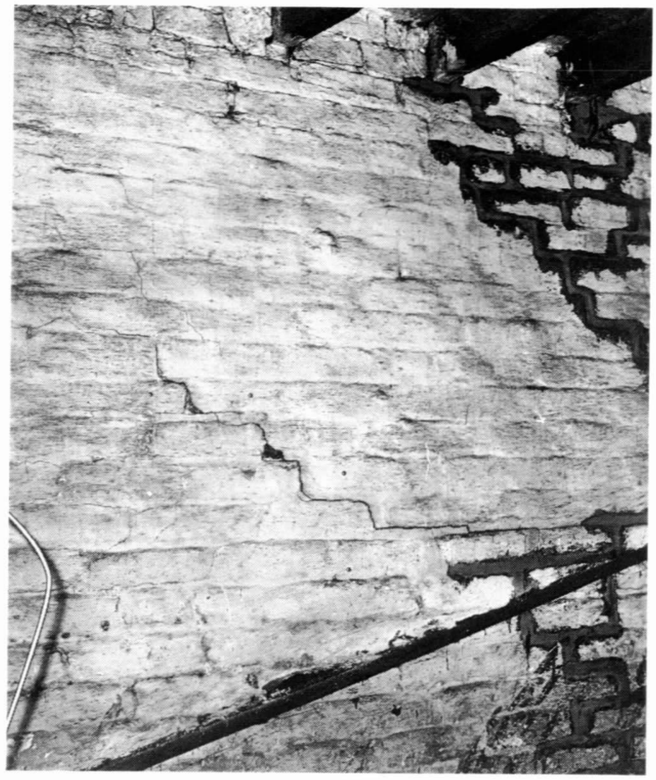


Plate 2 Side wall of Waggon Porch showing extensive cracking

Plate 3 Out of plumb wall adjacent to A47 at Thorney

Plate 4 15th century parish church adjacent to A16 at Louth

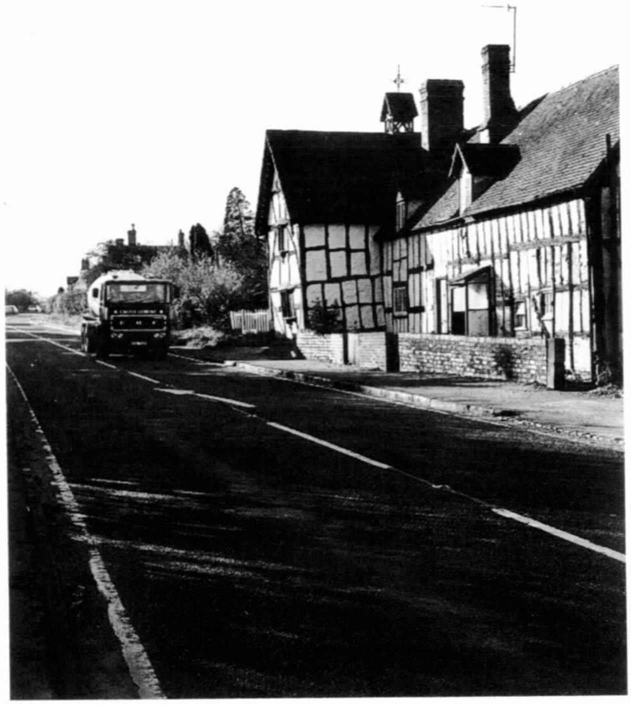


Plate 5 15th century timber framed building adjacent to A435 at Norton near Evesham

east end of this large building since some windows were heard to buzz and rattle as vehicles passed by. This anxiety was understandable since this end of the church is within two metres of the heavily trafficked A16 (Plate 4). Since the church was very large it was feasible to compare windows near the west end, which were not exposed to such high vibration levels, with the windows at the east end. Detailed examination showed that there were no differences in the condition of the windows which could reasonably be explained by exposures to traffic vibration.

Timber-framed cottage near Evesham, Warwickshire

This cottage was situated close to the heavily trafficked A435 and Plate 5 shows a pronounced distortion of the gable wall adjacent to the carriage way. Distortions of this type are not uncommon in this type of building and a similar building was found in Evesham which had even more severe distortion and yet was well removed from any main road. The cottage can be identified in a photograph published in a touring guide in 1954 and the distortion can be seen, although it is not possible to quantify the degree of tilt with any degree of accuracy. However it is evident that the distortion is not new and cannot plausibly be attributed to modern heavy traffic.

In these and all other cases it was concluded that the main causes of the damage observed were likely to have been site factors rather than exposure to traffic vibration.

4.6 REVIEW OF DATA ON VIBRATION DAMAGE IN HERITAGE BUILDINGS

This study was carried out under contract by Brian Morton and Partners. They approached over five hundred individuals and organisations throughout the world for relevant information on damage to heritage buildings that could possibly be attributed to exposure to traffic vibration. These sources included architects and surveyors who have responsibilities for cathedrals and churches, professional engineers and a range of organisations such as civic amenity societies who promote the conservation of these buildings. The information collected consisted mainly of bibliographic references and case histories of buildings of national importance. Replies were received to many of the letters and, in the cases where records were available and measurements had been taken, in-depth assessments were made. This involved visits to selected sites and where possible discussions were held with those who had been involved in damage assessment and measurement. In the case of Lincoln cathedral, the data available was substantial since a number of independent measurements of both vibration and settlement had been made during a period of over 20 years. The evidence for the assertion that old cathedrals and churches close to heavily trafficked roads show signs of excessive movement which can be attributed to the action of traffic vibration (Crockett, 1973) was also examined.

4.6.1 Results

From the very large amount of information received there were only a relatively small number of studies where damage, including excess tilting, was claimed to have been definitely caused by exposure to traffic vibration. From the available evidence these claims were not substantiated except in two cases. The first case is the fatigue study described in Section 4.3 where hairline cracking of plaster resulted from high levels of simulated traffic vibration. In the second case, damage to the flashings of the roof of Tower Bridge, London, was considered to have been caused by heavy vehicles using the bridge. It is likely that resonances were excited in the flexible bridge structure which resulted in high amplitude vibrations in the bridge towers. This mechanism is plausible but it is clear that the conditions that led to this damage are very unusual and that this effect could not occur adjacent to normal roads. There were many studies where vibration was thought to be a possible cause of damage either directly or in combination with other factors but no evidence was available to confirm or deny these impressions. Wherever evidence was available it suggested that traffic vibration was not the main cause of the damage observed.

4.7 DISCUSSION OF VIBRATION DAMAGE STUDIES

This report has described a number of different studies which attempted to determine the possible effects of traffic vibration on buildings. The fatigue test on a pair of semi-detached houses, where carefully controlled simulated traffic vibrations were generated, provided firm evidence that the direct effects of traffic vibration on a building in generally good condition is likely to be very small indeed. Despite the high levels of vibration, which would have proved intolerable to most occupants, there was only a small degree of damage. This consisted of hairline cracking of some plaster finishes which would probably have gone unnoticed in a normally decorated house. It was concluded that ground-borne vibration and not airborne vibration was responsible for this damage.

Some indirect effects of vibration were also expected since the building was on a medium density sand and it was thought that the ground-borne vibration would cause some densification of the sands under the foundations. The building was very carefully monitored for any movements and yet despite this there was no evidence of settlement occurring. However the individual test foundation strips did settle by varying amounts up to 14 mm due to soil migration: these strips moved by rotation and so there is a possibility that had the facade nearest the vibrator been less well tied to the rest of the building, or the sand had not been cemented at 1 m below the foundations, some movement might have taken place.

The pairwise comparison of buildings exposed to relatively high and low levels of traffic vibration were made at sites on generally soft alluvial type soils where it was considered that conditions were suitable for observing the effects of traffic vibration. The dwellings were built near the turn of the century and so it is likely that the buildings had been exposed to substantial traffic vibration over a period of many years. There was no evidence of excess structural damage at the exposed sites and a check on the vertical alignments of the front facades showed no significant differences except at the King's Lynn site. The exposed buildings at this site, unlike the control buildings, were tilting significantly towards the main road but this was considered to be due to the presence of an old badly filled drainage ditch at the front of the properties. This contained very soft soil and fill material and was thought to be the most probable cause of the foundation movements.

The case studies of heritage buildings did not produce any firm evidence that the building defects had been caused by traffic vibration. It was more likely that poor ground conditions and ill advised alterations were the major causes of significant damage in many cases. In addition, the review of the available information from sources worldwide did not produce any substantive evidence of damage to buildings caused by traffic running on normal roads.

In the studies described considerable efforts were made to examine buildings under 'worst case' conditions. These have failed to show any significant effect of traffic vibration on ordinary domestic dwellings or heritage buildings. Thus the evidence does not support the assertion that traffic is responsible for major damage. However, at sites exposed to very high levels of ground-borne vibration for a substantial period, some minor damage to plaster finishes could occur. The risk of damage would obviously be greater if the plaster work was in a fragile condition. Additionally, there may possibly be soil conditions that could be susceptible to settlement produced by high levels of traffic-induced ground-borne vibration. A further possibility is that traffic vibration could exacerbate damage effects due to other causes. In all the studies no evidence of these effects were found in buildings, but some newly constructed foundation strips on uncompacted sand did settle up to 14 mm.

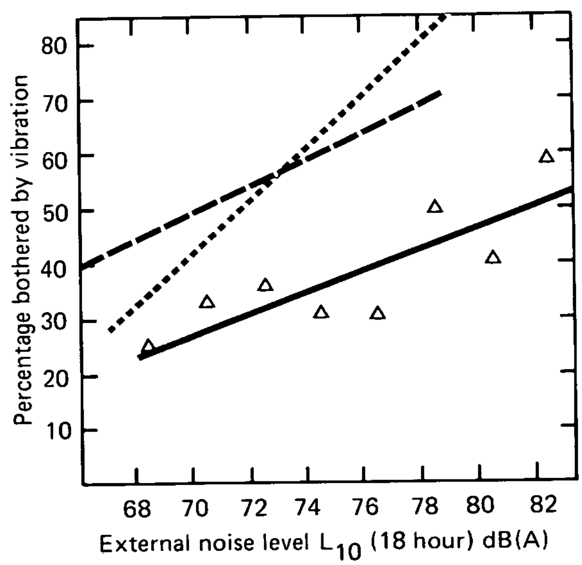
5 METHODS TO AMELIORATE THE EFFECTS OF TRAFFIC VIBRATION

There are a number of strategies that can be adopted to reduce the nuisance caused by traffic vibration. The type of action will depend on whether the problems are produced by airborne or ground-borne vibration. A reasonable initial approach would be to establish by simple observation, prediction or by suitable measurements, the contribution from each source. A site visit during a period when HGVs or buses are frequently passing the site is most useful. If it is established that the main manifestations of vibration are windows or doors that rattle and buzz in rooms fronting the main road then it is likely that airborne vibration is a problem. In contrast, ground-borne vibration often produced a short duration impulsive vibration which is most readily detected in the middle of upper floors. This should be distinguished from a longer duration, higher frequency, trembling of the floor which may sometimes be produced by high levels of low frequency noise. A ground-borne vibration problem is most acute where the building is within a few metres of a significant road surface irregularity such as a poorly backfilled trench or sunken cover. Section 3.2.3 describes a method for predicting the likely level of nuisance due to airborne vibration and Section 3.4.4 develops a predictive equation which determines whether ground-borne vibrations are likely to be intrusive. Measurements of peak particle velocity at the front foundations will indicate that ground-borne vibration is a problem if levels are significantly above 0.3 mm/s and the dominant frequency is in the range 8–25 Hz. Possible methods to reduce the nuisance are discussed below, grouped by type of vibration.

5.1 AIRBORNE VIBRATION

Low frequency noise readily affects light, flexible structures such as doors and windows particularly if they are loose fitting and therefore have a degree of freedom of movement. Some older sash windows are particularly prone to rattle and buzz. In cases where this appears to be the main source of annoyance, an obvious solution is to wedge the offending frame or glass to prevent movement. However it can sometimes prove hard to locate the exact source of this parasitic noise. This is particularly difficult when the noise occurs only occasionally. Opening windows in modern thermal double glazed units are by comparison usually well fitting and should be less prone to producing annoying vibrations. Low frequency noise is attenuated to a greater extent when passing through such double panes of glass and an additional reduction of 3 to 5 dB can be expected from these replacement windows. Double windows fitted as part of the remedial package provided under the Noise Insulation Regulations are also likely to reduce nuisance although the low frequency noise reduction is generally less. These reductions are clearly not large and can obviously be degraded if windows are opened. It should be noted that low frequency noise can be perceived directly and can sometimes lead to annoying muffled sensations in the ears and perceptible chest vibrations.

Figure 14 shows the trend in the percentage of residents 'bothered by vibration' with noise exposure level. The TRRL data was taken as part of the 50 site survey where most dwellings had single glazing. This data is compared with results from a Building Research Establishment survey (Utley et al, 1986) where all dwellings were fitted with double windows which had been installed as part of the insulation package available under the Noise Insulation Regulations. The TRRL survey



BRE data. Houses along dual carriageways fitted with double windows Y=1.9X - 105.6; r=0.83

TRRL data, Houses along dual carriageways, mainly single glazing: Y=4.71X - 287.4; r=0.90

TRRL data. Houses at all sites, mainly single glazing: Y=2.36X - 116.0; r=0.64

Fig.14 Percentage of respondents bothered by vibration
Source: Utley et al 1988

included a wider range of road types than the BRE survey and therefore the results from dual-carriageway sites, which are likely to be similar to the BRE sites, have been considered separately. Whichever of the sets of data from the TRRL survey is used, there appears to be a considerable reduction in the number of people bothered by vibration in dwellings where the insulation package has been installed. At a L_{10} (18-hour) dB(A) level of between 72 and 74 dB(A) at the facade, the percentages bothered reduces from approximately 55 to 30 per cent.

Two main approaches can be adopted to reduce the problem at source. Firstly, it may be possible to reduce the number of heavy vehicles at problem sites by various traffic management schemes. Section 3.3.2 describes an equation which allowed the prediction of the median vibration nuisance score from the number of HGVs passing the site in an 18 hour day and the distance from the front facade of the building to the edge of the carriageway. The dependence on lorry flow is logarithmic so a substantial reduction in flow would be needed to effect a noticeable improvement. Secondly, a long term approach, but one which would produce general improvements, is to reduce the low frequency emissions from vehicles. Such controls would, however, require the development of new test procedures and, additionally, the setting of limit values would require new regulations to be developed and agreed internationally. It should be noted that noise barriers designed to screen traffic noise may be of limited use in reducing airborne vibration problems since there is typically little attenuation of the low frequency sound which is responsible for perceptible vibration effects.

5.2 GROUND-BORNE VIBRATION

There are a number of approaches that can be adopted to reduce the exposure to ground-borne traffic vibration. In this case it is easier to make reductions at source rather than attempt to attenuate the transmission of these vibrations into buildings.

5.2.1 Reductions at source

An obvious remedy is to ensure that a smooth road surface is maintained where dwellings and sensitive work areas are close to the road since irregularities of the order of 20 mm in the surface profile can produce perceptible vibrations in buildings located within a few metres of the carriageway. On soft soils such as peat and alluvium there is a greater need to ensure a smooth surface because of the greater response of the ground.

Generally, peak particle velocities increase with speed for all vehicles and therefore there should be some advantage in reducing the maximum permissible speeds of HGVs past sensitive sites. An estimate of the likely reduction can be obtained from the trend with speed shown in the predictive equation developed in Section 3.4.4. Reducing the maximum speed of these vehicles from say 80 km/h to 48 km/h should decrease peak particle velocity by 40 per cent. This may bring substantial relief if the resulting peak velocities fall below the perception threshold.

Decreasing the load carried on a particular HGV does not necessarily reduce the peak particle velocity and in some cases an empty lorry can produce higher levels than when fully laden (Watts, 1988a). However, smaller vehicles do tend to induce smaller vibrations as can be seen in Figure 7 which shows a clear trend of rising PPV with increases in gross vehicle weight. A typical gross vehicle weight restriction on public roads is 7.5 tonnes, and provided maximum speeds do not rise when the weight limit is reduced, the expected peak velocity, based on the regression line, would be reduced substantially.

A measure that may have benefits in the long term is the design and regulation of HGV suspensions to reduce the generation of vibration. Tests on HGV vehicle suspension systems have shown that different systems loaded to similar axle weights produce some differences in the peak levels of vibration (Watts, 1988a) and so there appears to be some scope for improvement.

5.2.2 Attenuation methods

One possible technique to control ground vibration is to construct a trench between the source and affected buildings. The trench acts as a barrier to vibration and can therefore reduce transmission through the soil. To obtain maximum performance the impedance of the fill material used in the trench should be as low as possible so energy is reflected rather than transmitted towards the affected building. A possible fill material is expanded polystyrene which has a low impedance, is inexpensive and is also strong enough to withstand soil pressures within the trench. However, in a study by Hood and Marshall (1987) a polystyrene filled 3 m deep trench produced only a 15 per cent reduction in vibration at a distance of approximately 40 m from the trench, although higher reductions were recorded close to the barrier. Other experiments, involving trenches and sheet piling, have shown varying degrees of success (Barkan, 1966; Richard et al, 1970; Liu et al, 1974). Since surface ground waves produce significant disturbances down to about a third of a wavelength, which for some ground waves may be greater than 10 m, it is clear that to achieve significant attenuation of low frequencies very deep trenches would probably be needed. These results suggest that it is unlikely that such a technique would be commercially viable for screening conventional dwellings from traffic vibration. The technique may, however, offer a more attractive solution at sensitive locations where other forms of building isolation prove to be either too expensive or fail to achieve an acceptable degree of control.

A further method of attenuation is to isolate the affected building by decreasing the natural frequency of the building to below that of the vibration source. In this way the transmission of the vibration into the building can be reduced. This has apparently been carried out successfully by introducing rubber mounts into the foundations (Crockett, 1985; Grootenhuis, 1979). Again this is an expensive solution for existing buildings and could probably only be justified for very sensitive locations. Costs would probably be much lower where the system formed part of the design of a new building.

If the main problem is the detrimental effect of vibration on the performance of sensitive equipment it should be possible to provide local passive isolation by mounting the apparatus on suitable isolators. Isolation systems have utilised a range of materials and techniques including cork, rubber, helical springs and pneumatic devices (Ferahian and Ward, 1970). Measurements have shown that in domestic buildings at least, vibrations on ground and basement floors tend to be significantly lower than on suspended floors at higher levels in the building and therefore it may be possible to reduce the problem simply by relocating the equipment to these lower floors.

6 CONCLUSIONS

This report describes a number of studies of the effects of traffic-induced vibrations on people and buildings. Methods are described which allow the prediction of nuisance from airborne and ground-borne vibration and possible methods to ameliorate the environmental impact. The results should also be of assistance in the planning process in that proper weight can be given to the likely environmental impact of traffic vibrations on buildings. The main conclusions are as follows:—

6.1 VIBRATION LEVELS

1. Overall, fewer people are bothered by vibration from traffic than by traffic noise. However, the proportion of residents seriously bothered by vibration (8%) is similar to the percentage seriously bothered by noise (9%).

2. A majority of residents interviewed in a survey on traffic vibration said they were bothered by vibration because they thought it could cause damage to their properties.

3. Where vibration nuisance is caused mainly by airborne vibration, it is the low frequency content of the noise which causes the problem. Nevertheless, standard acoustic indices, which cover the whole spectrum of noise, were found to be significantly correlated to the average level of vibration nuisance at residential sites. These indices were generally better predictors of disturbance than were measures of window vibration, traffic flow or road roughness. However a composite measure of heavy vehicle flow and distance of the affected building from the carriageway was as good a predictor of vibration nuisance as was the best acoustic measure. The L_{10} (18 hour) dB(A) index was among the best correlated acoustic measures and since it is in widespread use it would be suitable for prediction purposes.

4. Ground-borne vibration affects only a small proportion of residents. However, the peak levels of these vibrations at building foundations can be relatively high, especially where the underlying soil is soft and houses are close to significant road surface irregularities. Peak levels up to ten times the level of perception have been recorded and in these situations serious nuisance and anxieties about building damage are likely to arise.

5. A prediction equation has been developed which enables the likely maximum peak vertical particle velocity at the foundations due to ground-borne vibration to be estimated. The parameters of importance include the maximum speed of HGVs, road surface profile, and ground conditions. The type of underlying soil was found to greatly influence the level of vibration and the largest response was recorded on soft soils such as alluvium and peat deposits.

6. Sensitive equipment and critical work areas can be affected by very low levels of vibration close to the level of perception. General guidance on tolerable levels for satisfactory equipment performance is of limited value since the instrument design and mounting conditions are critically important in determining the degradation of performance under vibration. Manufacturers may sometimes provide guidance on the maximum permissible levels of vibration.

6.2 EFFECTS ON BUILDINGS

A number of studies have been carried out to determine the possible effects of traffic vibration on a range of building types. In addition, a worldwide search of possible sources of information has been made. The conclusions of these studies are as follows:—

7. In a fatigue damage study where a recently vacated house was exposed to relatively high simulated airborne and ground-borne traffic vibration over a prolonged period only non-structural damage was found to have occurred. This was caused by ground-borne vibration and was limited to a small amount of fine plaster cracking. It is unlikely that this damage would have been recognized in a normally decorated house. There was no evidence that exposure to airborne vibration had caused even minor damage. There was no settlement of the house foundations due to the action of vibration. Some movement had been expected since the test house was built on medium density sand and there was the potential for some densification of soils beneath the foundations.

8. In studies of occupied buildings on relatively soft soils, where the degree of damage was compared in groups of similar houses adjacent to and remote from heavily trafficked roads, it was found that there was no significant difference in the condition of the two groups of buildings. This was despite the fact that 'worst case' conditions could reasonably be considered to have been studied.

9. Case studies of eight heritage buildings of widely different ages, size, and type of construction exposed to relatively high levels of traffic vibration revealed that there was no evidence that traffic vibration has caused the observed damage. The defects could more plausibly be explained by site factors other than traffic vibration.

10. A worldwide search for sources of relevant information on vibration damage in heritage buildings did not reveal any evidence that damage had been caused by exposure to traffic vibration.

These findings on traffic vibration damage therefore lead clearly to the overall conclusions that there is no evidence to support the assertion that traffic vibration has a significant damaging effect on buildings. There is evidence that a small amount of superficial damage could be produced by sustained exposure to very high levels of ground-borne vibration, but it is likely that action would be taken to limit vibration levels if these circumstances ever arose in domestic properties since the level of nuisance would probably be intolerable to most occupants.

6.3 ALLEVIATION OF TRAFFIC VIBRATION

Methods to ameliorate the effects of traffic vibration depend on whether the problem is largely due to airborne or ground-borne vibration. The following conclusions can be drawn from the various studies:—

11. Where the vibration is largely airborne, window rattle can give rise to nuisance and better fitting windows may improve the situation. Double windows and double glazed windows are likely to reduce vibration nuisance. A reduction in the number of HGVs passing the site is likely to decrease the level of disturbance, but, because of the logarithmic dependence of average nuisance on lorry flow, the reduction would have to be large to produce a significant decrease in disturbance.

12. If ground-borne vibrations are the major concern, then there are a number of remedial measures that can be taken. The simplest approach would be to reduce the problem at source. This can be achieved, for example, by removing significant surface irregularities in the road surface near the affected properties. Other approaches are to reduce the speed of HGVs near the properties, re-route the HGVs to less sensitive roads and introduce a limit on gross vehicle weights of about 7.5 tonnes. The attenuation of ground-borne vibrations by filled trenches and the isolation of buildings by resilient mounts are further conceivable solutions, but these are likely to be expensive. If sensitive equipment is adversely affected then it should be possible to provide local passive isolation by the provision of suitable mounts that will substantially reduce the effects of vibration.

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