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TRAFFIC VIBRATION AND BUILDING DAMAGE
(An examination of the need for further research)

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INTRODUCTION

Previous studies at the Transport and Road Research Laboratory on the subject of traffic vibration have concentrated on examining the causes of building vibration and the overall disturbance caused by vibration [1,2,3]. During the course of these studies it has become apparent that numbers of people who experience some form of traffic vibration in their homes consider that this can, or already has, caused damage to their property. Increases in allowable vehicle weights may have tended to intensify the degree of concern [4,5].

While there is plenty of evidence of damage to buildings, there is little evidence linking traffic vibration to this damage and since traffic vibrations are generally very low, it has become common practice to place the blame for observable building damage on a wide variety of natural causes which cause substantially higher stress levels in structures than traffic vibration. While this argument would seem plausible, it does ignore the possibility that fatigue damage could occur as a result of long term exposure either to low level stress reversals or to a combination of such reversals and high static stresses in the structure. It is also possible that, on some soils, traffic vibration could cause compaction or soil movement beneath the foundations leading to settlement and damage, or at least to high static stresses.

This paper briefly reviews the reasons why new research on traffic vibration has been started at TRRL and gives an outline of experiments which are being carried out to gain a better understanding of the problem.

THE EVIDENCE AGAINST TRAFFIC RELATED VIBRATION DAMAGE

Sources of traffic vibration

Traffic can cause vibrations in building by two separate processes:

1. Low frequency sound waves generated at vehicles exhausts can couple into the structure via windows and doors causing different elements of the building to vibrate.
2. Forces generated by vehicles passing over the road surface profile can generate vibration in the ground which then propagates along the ground surface and through the underlying soil to reach the building foundations.

The low frequency sound waves of importance have frequencies centre on the fundamental exhaust frequencies of heavy duty diesel powered lorries (ie the range 50-100 Hz). Even when heavy lorries travel close to buildings and where the sound pressure levels are high, the forces induced in the structure are small. Nevertheless these forces can give rise to perceptible vibration, particularly, in the lighter and more flexible parts of the structure such as windows and suspended floors. In addition, poorly fitting windows can be made to rattle or buzz as a result of low frequency noise excitation which can be annoying to the occupants. Vibration generated in the floors by low frequency noise will depend upon the mass and stiffness of the structure and the frequency of the noise will depend upon the mass and stiffness of the structures and the frequency of the noise as well as the dimensions of the room which can give rise to standing wave effects. Again, while these vibrations can, on occasions, be detectable and can give rise to disturbance, the stresses induced in the floor, its support and the adjoining walls are small and generally lower than the levels caused by normal household activities such as opening and closing doors or the operation of domestic appliances.

Ground vibrations generated by traffic do not generally become perceptible unless the nearby road is in a poor condition, usually exhibiting irregularities in the surface such as a poorly filled trench or pothole. Vehicles passing over the surface irregularity produce impulsive forces in the road whose decay characteristics depend upon the resonant frequencies of the suspension and tyre (ie the wheel hop frequency) and the damping characteristics. For many vehicles, the suspension frequencies lie in the range 10-20 Hz which means that even for low vehicle speeds, the surface irregularity may produce relatively high dynamic loads over several metres of the road. The dynamic loads depend mainly upon the type of vehicle, its suspension and speed but typically the ratio of dynamic axle load to static axle load would be 1.5 to 2.0 with a possibility of an impact factor rising to 3 on occasions [6]. The dynamic load imparted to the surface may, therefore, be as high as 10-20 tonnes given the current axle loads permitted on UK roads.

However, despite the large forces resulting from this dynamic loading the average vibration levels generated in the ground alongside the road are usually quite low (ie less than 100 mms/s^2) although distinctly perceptible under some conditions. Figure 1 shows an example of vibration recorded in the ground at a distance of 6.9 metres from a large road surface irregularity during the passage of a two-axle lorry. The first major peak represents the impulse generated by the first axle (static load = 5.94 Mg) as it passes over the irregularity followed by three further peaks. This is then followed by the impulse generated by the second heavier axle (static load = 9.70 Mg) and further peaks decreasing according to the damping characteristics of the suspension and tyres on the vehicle and the response of the road structure and the soil beneath. In general, a maximum of three or, possibly, four major peaks may be generated by the passing of each axle. On a three or more axled vehicle impulses occur more rapidly and interference between vibration waves often result in fewer observed peaks per axle. For example, at this site, a 5-axle vehicle was observed to produce 11 major peaks.

<u>Damage criteria</u>

A great deal has been written about the levels of vibration which could give rise to damage in buildings. While it is unlikely that a precise and universally acceptable set of criteria will emerge, the consensus would appear to suggest that the levels required to cause even minor damage to structures are generally much higher than the levels generated by traffic. In addition, it should be borne in mind that damage criteria have, not unnaturally, tended to be of a conservative nature. For example, the original German Standard DIN 4150 (1938) gave limits which are generally regarded as over cautious. The Standard was revised in 1984 and provides some relaxations from the original limit values as well as providing different criteria for different frequency ranges [7]. Table 1 summarises the recommendations for peak particle velocity for transient shaking.

Table 1. Guide values for peak velocity during transient shaking (DIN 4150)

Structure Type	Peak particle velocity guide values (mm/s)			
	Foundations			Top storey on wall at floor level (all frequencies
	<10 Hz	10–50 Hz	50–100 Hz*	
Offices and industrial premises	20	20–40	40–50	40
Domestic houses and similar constructions	5	5–15	15–20	15
Other building sensitive to vibrations	3	3–8	8–10	8

*At frequencies higher than 100 Hz a higher guide value is allowable.

The various recommendations and criteria for prevention of damage are borne out by the results summarised in Figure 2 which is a compilation of vibration from sources which have been related to damage [8], vibration from various sources which has not caused damage [8] and vibration from traffic [9]. In each case the vibration level was measured on a structural element, for example, a foundation, wall or floor. It would appear that the onset of damage occurs at a particle velocity of about 10 mm/sec which is substantially above the average or RMS levels generated by road traffic.

THE EVIDENCE FOR TRAFFIC RELATED DAMAGE

Possible damage mechanisms

While it would appear that for most materials in buildings, the levels of vibration from traffic are too low to cause direct failure, it is important to realise that the vibration velocities known to occur at the roadside may have little relation to the vibration levels that propagate into nearby buildings. Propagation of vibration into soil and rock is very complex, involving the interaction of both shear and compressional body waves which propagate with different phase velocities. The influence of boundaries within the soil structure can also give rise to reflections, refractions and scattering and associated interference effects. The presence of a surface introduces a third wave type, the Rayleigh Wave, which travels at a lower phase velocity than the compressional body waves and is potentially more damaging to structures since the wavelength is relatively small. In addition this wave is confined to a wavelength or so of the surface and is, therefore, subject to relatively low spreading losses. The excitation of a building structure is also very complex and will greatly depend on the response characteristics of the different building elements. In many cases, resonance of the floor will occur at frequencies in the range 10–30 Hz which is consistent with the suspension frequencies of heavy vehicles. Because of this the amplitude of vibrations of floors or ceilings can be four or five times that of the building foundations.

It is also important to realise that characterising vibration by an RMS average in, say, the vertical direction does not always indicate its true significant or damaging potential. Many previous measurements of traffic vibration have been carried out near roads with smooth surfaces and often RMS vibration levels have been recorded. Recently a study of traffic vibration [10] at kerbsides and in buildings close to significant road surface irregularities has recorded peak levels of well in excess of 100 mm/sec^2. It can be seen, for example, in Figure 1 that the peak particle velocity of the vertical direction waveform recorded close to the road was 286 mm/s^2. If this occurred on a lightly damped soil and near a building it could produce vibrations in the structure which equal or exceed the published thresholds for architectural damage. The highest level recorded at the kerbside in this recent study was over 1200 mm/s2. Table 2 lists the peak acceleration levels recorded in buildings close to surface irregularities.

Table 2. Peak acceleration and dominant frequency by site

Site	Vehicle producing vibration	Max depth of surface irregularity (mm)	Position	Peak acceleration level (mms^{-2})	Dominant frequency (Hz)
A	5 axle artic	-32	Facade*	75	12
			Floor**	175	12/74
B	2 axle rigid	-75	Facade	130	12.7
			Floor	164	12.5
C	3 axle cement mixer	-28	Facade	110	13
			Floor	114	12.5
D	4 axle rigid	-23	Facade	42	60
			Floor	78	25.5
E	Double decker bus	-15	Facade	57	10
			Floor	96	24

*Near foundations at the facade fronting the main road.
**In the middle of the living room.

The highest level recorded in the hard structure of these buildings was 130 mm/s^2 (site (B), which according to the data given in Figure 2 is approaching the levels at which vibration damage begins to occur.

While some doubts must, therefore, be directed at the observation that traffic vibration does not exceed damage thresholds in all circumstances, a further and more widespread concern is the possibility of fatigue damage occurring as a result of continuous exposure to low levels of vibration over a long period of time. It is worth noting that buildings located alongside busy roads may be exposed to many millions of cycles of fluctuating stress from traffic each year and so the number of repeat loadings can be very high over the expected life of a building and some fatigue, therefore, a distinct possibility. Furthermore, the possibility must be considered that damage may be caused by a "trigger" effect whereby an already weakened component may fail at an earlier stage than would have occurred in the absence of traffic vibration.
In addition to these direct causes of damage, it is also possible that damage occurs indirectly as a result of vibration aided compaction of soils beneath the foundations of buildings. Such assisted settlement, if occurring, could lead to progressive damage of buildings, particularly if the foundations settle at different rates in relation to the vibration stresses occurring in the soil. For example, vibration levels will generally be higher at the front of the building than at the rear. Buildings which are at greatest risk from settlement are those constructed without proper foundations on poorly consolidated soils. Differential settlement has been suggested as a reason why several larger churches and medieval cathedrals apparently lean towards the

nearest heavily trafficked road [11], however, it is not possible with the available data to substantiate these claims.

Perceptions of vibration damage

It is quite clear that despite the evidence that traffic vibration does not produce stresses in structures which are large enough to cause damage directly, large numbers of people believe that it does. There is considerable anecdotal evidence, and the numbers of complaints and claims received by both the Department's of Transport and of the Environment as well as by the local authorities provide further evidence of this widespread view. In addition, there is more substantive evidence taken as part of a recent survey at fifty sites [3] where residents were interviewed about their perceptions and concerns with vibration. At each site some thirty residents from different households were interviewed (ie a total of some 1500 interviews). The percentage of respondents who noticed traffic vibration in their homes is summarised in Table 3.

Table 3. Percentages of respondents who noticed various vibrations (all sites combined) (Reference 3)

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 in the chest	18.9
Feeling vibration in the air	30.2

It can be seen that a large proportion observed windows and doors rattling and buzzing and perceived the floor shaking or trembling. Table 4 lists the percentage of residents who reported various types of damage thought to be caused by traffic vibration

Table 4. Percentages of respondents reporting damage thought to be caused by road traffic (Reference 3)

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

A significant proportion reported minor damage such as cracked plaster or tiles falling off the roof while, surprisingly, 14 per cent reported that subsidence had occurred which could lead to more serious forms of damage. While it is clear that people do tend to overstate the evidence of traffic vibration damage, and the responses should, therefore, not be taken as evidence, by itself, of a significant effect, the data does provide a further reason, coupled with those given in the previous section for developing further research on this topic.

EXPERIMENTAL DESIGN CONSIDERATIONS

Any research method has to overcome the very difficult nature of the problem. Damage from traffic vibration is likely to be slow acting, if occurring at all, in some cases requiring many years to develop into measurable effects. There are also many natural causes of damage and so the research method must be capable of isolating the vibration damage component from the many other factors which are acting simultaneously. In addition it is necessary to determine and assess the type of damage occurring and to relate this to the mechanisms of damage which have been suggested.

No single experiment can be expected to yield all the answers to the questions raised. Furthermore, the techniques of assessing and measuring damage in buildings have yet to be developed for this application. It was, therefore, considered necessary to design and to develop appropriate techniques as part of a feasibility study with the hope that this would give an early indication of the extent of the problem and would give further guidance on the design of a second stage of experimentation.

Three different experiments were proposed:

1. A fatigue study to be carried out on an unoccupied dwelling using simulated traffic vibration inputs. The objective would be to isolate traffic vibration effects from other long term "environmental" effects and, in particular, to determine the levels of traffic vibration needed to cause damage of any classification in buildings, the location of this damage and the relative importance of ground and airborne vibration on the total damage caused.
2. An assessment to be carried out using occupied dwellings in order to establish clearly whether excess damage due to traffic vibration occurs in real environments. In this case the objective would be to compare the structural quality of buildings exposed to heavy traffic flows and high levels of vibration with essentially identical buildings located in a quiet area away from the traffic. Again techniques would need to be developed for assessing damage in occupied dwellings.
3. An examination for evidence of trigger damage to be carried out in buildings located alongside a road in which traffic flows were about to increase. A sample of buildings could be studied before and after the increase in traffic flow.

At present the first experiment to study damage mechanism using simulated traffic vibration on a test house has been completed and the second experiment to study damage in occupied houses is in progress.

Reference 12 describes the experimental method used to study the test house and references 13 and 14 describe the results. It should be noted that very little damage was recorded in this house despite the fact that the simulated vibration levels were at the extreme end of the range observed in practice.

CONCLUSIONS

While, in general, the levels of traffic induced vibration in buildings are too low to cause damage directly, little is known about the possibility of long term exposures causing fatigue in parts of the structure or of the potential for traffic vibration to cause buildings to subside by compacting the soil beneath the foundations. Further research on these topics is currently being carried out at the Transport and Road Research Laboratory.

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REFERENCES

[1] D.J. Martin, P.M. Nelson and R.C. Hill, 'Measurements and anlysis of traffic induced vibration in buildings', TRRL Supplementary Report SR 402, (1978).

[2] D.J. Martin, 'Low frequency traffic noise and building vibration', TRRL Supplementary Report SR429, (1978).

[3] G.R. Watts, 'Vibration nuisance from road traffic - results of a 50 site survey', TRRL laboratory Report LR 1119, (1984).

[4] Civic Trust, 'Heavy lorries', A Civic Trust Report, (1970).

[5] A. Armitage, Chairman, 'Report of the inquiry into lorries, people and the environment', London (HMSO), (1980).

[6] D.R. Leonard, J.W. Grainger and R. Eyre, 'Loads and vibration caused by eight commercial vehicles with gross weights exceeding (32.5 Mg)', TRRL Laboratory Report LR 582, (1974).

[7] DIN 4150, 'Vibrations in buildings - effects on structures', Deutsch Norm, (April 1984).

[8] R.J. Steffens, 'Effects on buildings of vibrations caused by traffic', Building Science, 6, (1971).

[9] A.C. Whiffin and D.R. Leonard, 'A survey of traffic induced vibrations', TRRL Laboratory Report LR 418, (1971).

[10] G.R. Watts, 'Traffic induced groundborne vibrations in buildings', TRRL Research Report RR 102, (1987).

[11] J.H.A. Crocket, 'Some practical aspects of vibration in Civil Engineering', pp 267-272, Butterworths, London, (1966).

[12] R.A. Hood and C. Marshall, 'Monitoring the effects of simulated road traffic vibrations on a test house - experimental methods', Paper presented at Acoustics '87, (1987).

[13] C. Marshall and R.A. Hood, 'Monitoring the effects of simulated road traffic vibrations on a test house - results', Paper presented at Acoustics '87, (1987).

[14] G.R. Watts, 'Response of building elements to simulated traffic vibrations', Paper presented at Acoustics '87, (1987).

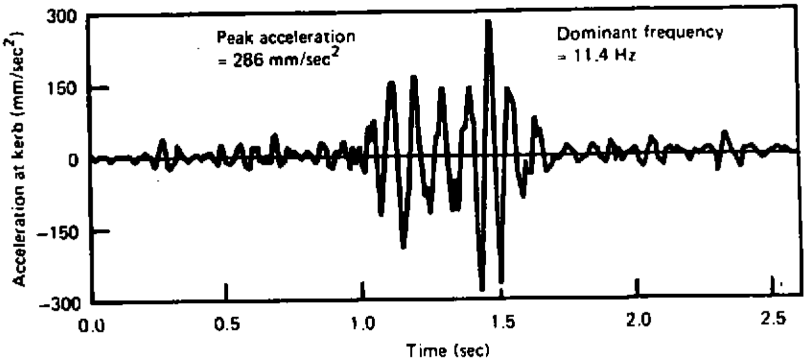

Fig.1 Time record of acceleration close to surface irregularity produced by a 2 axle truck

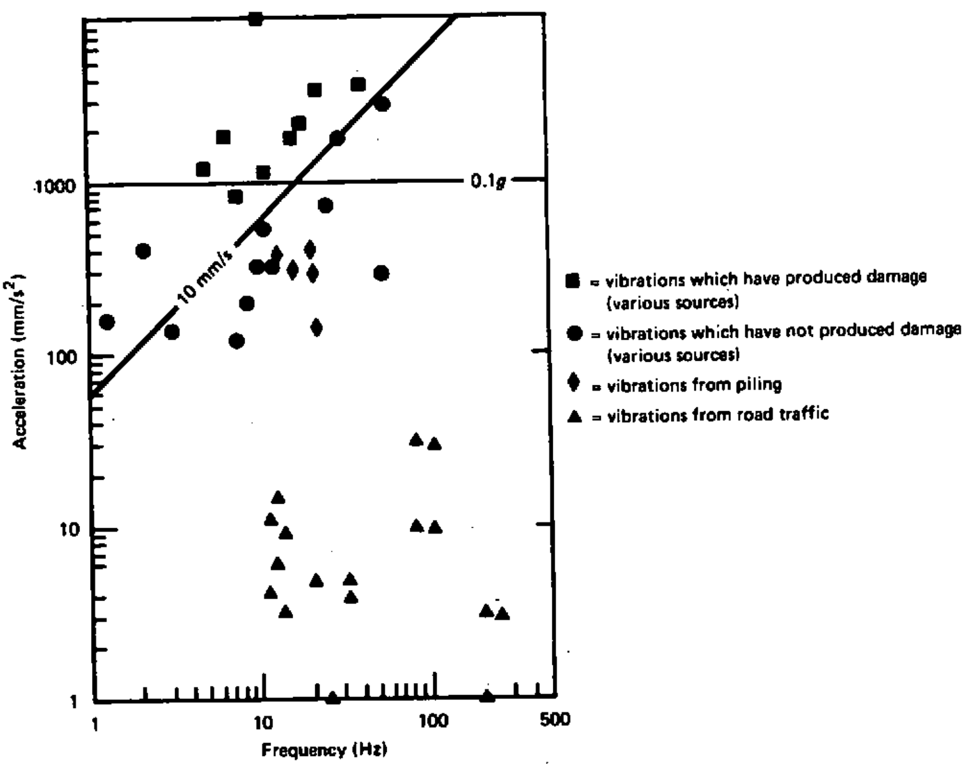

Fig.2 Measured building vibrations and building damage