LOW FREQUENCY TRAFFIC NOISE AND BUILDING VIBRATION

by

D J Martin  BSc PhD MInst P

Any views expressed in this Report are not necessarily those of the Department of the Environment or of the Department of Transport
Ownership of the Transport Research Laboratory was transferred from the Department of Transport to a subsidiary of the Transport Research Foundation on 1st April 1996.

This report has been reproduced by permission of the Controller of HMSO. Extracts from the text may be reproduced, except for commercial purposes, provided the source is acknowledged.
CONTENTS

Abstract
1.
1. Introduction
2.
2. Human response to vibration
   2.1 Laboratory studies
   2.2 Social surveys
3.
3. Experimental measurements
   3.1 General
   3.2 Description of sites
   3.3 Measurement and analysis techniques
4.
4. Results of measurements
   4.1 Excitation of floor vibration by low frequency vehicle noise
   4.2 Long term statistical averages
5.
5. Discussion
6.
6. Conclusions
7.
7. Acknowledgements
8.
8. References

(C) CROWN COPYRIGHT 1978

Extracts from the text may be reproduced, except for commercial purposes, provided the source is acknowledged
LOW FREQUENCY TRAFFIC NOISE AND BUILDING VIBRATION

ABSTRACT

Building vibrations caused by heavy traffic close to buildings in urban areas were investigated at four sites where a high degree of vibration bother had been demonstrated or was expected. It was found that low frequency acoustic excitation was responsible for floor vibrations at all sites. Floor vibrations were generated in two frequency ranges. These were at 63 – 125 Hz which corresponded with the excitation frequencies of exhaust emissions, and at 10 to 25 Hz which corresponded with the natural frequencies of the upper freely-suspended floors at the sites. The use of vibration perception thresholds to describe criteria for bother is discussed. It is suggested that the mechanism of vibration disturbance may be a complex combination involving structural vibration and low frequency sound which may be either heard or felt as body vibration.

1. INTRODUCTION

Many effects of road traffic in urban areas have been studied in recent years. Among the factors which are sources of disturbance to people are traffic noise and traffic-induced vibrations in buildings. Noise is closely related to vibration and they are not always distinguishable. Both noise and vibration may be directly experienced as unpleasant sensations, and vibration can further disturb people because of fears of damage to the building fabric. The overall extent of traffic vibration disturbance can be estimated from a national survey of traffic nuisance, carried out in 1972. The survey showed that whilst vibration was less widespread than noise, being experienced often by only ten per cent of those interviewed, in the situations where vibration was encountered it was considered to be a serious source of bother by those affected. Potentially, therefore, traffic induced vibration disturbance presents almost as widespread a problem as traffic noise by which one in ten of the population would claim to be seriously disturbed.

Traffic-induced vibrations can be generated in buildings either by ground-borne vibrations or by air-borne low frequency sound. It has been established that ground-borne vibrations originate with the variation in contact forces between the wheels of a vehicle and the road surface. However, when a road conforms to the Specifications for Road and Bridge Works as regards surface finish, moving vehicles do not normally generate vibrations in the road surface which are large enough to be perceived by people alongside the road. It is unlikely, therefore, that ground vibrations can cause perceptible structural vibrations in buildings located near to a well maintained road with a smooth surface.

Air-borne low frequency sound in the frequency region below 100 Hz can also induce building vibration. Acoustic coupling of sound waves through apertures such as windows can excite the window pane and the contents of the room into vibration. Resonances may be produced when the sound wave frequency corresponds to a natural frequency of the structure being excited. The occupants of buildings exposed to high levels of low frequency sound may detect vibration by direct perception in the body, by indirect perception of the vibratory responses of parts of the building or by a combined response involving both direct and indirect perception.

This report describes measurements of low frequency sound and building vibration carried out at four sites.
These sites were chosen where:

(1) the road surface was smooth and there were no surface discontinuities present which could give rise to substantial ground-borne vibrations in the test buildings, and

(2) it was expected that the level of structural vibration would give rise to a high degree of bother.

The aims of this study were to:

(1) determine the levels of floor vibrations occurring at four sites where the principal cause of structural vibration was low frequency sound emitted from road traffic, and

(2) examine the suitability of the measures of vibration adopted to predict disturbance at sites where a high degree of vibration bother was expected.

2. HUMAN RESPONSE TO VIBRATION

2.1 Laboratory studies

Direct mechanical vibration of the body has been studied as a means of deriving criteria for passenger comfort in vehicles. These studies have usually employed human subjects in laboratory experiments where the subject sits or stands on a vibrating platform. Human sensitivity to continuous sinusoidal vibrations has been expressed in terms of RMS acceleration level as a function of frequency for various degrees of disturbance.

An International Standard for the evaluation of human exposure to whole body vibration has been produced using results from studies of the type described above. An amendment to this standard proposes limits for acceptable vertical vibrations for people in buildings. These limits are based on the thresholds of vibration perception, and are defined in the frequency range between 1 and 100 Hz.

In order to determine whether a given level of traffic-induced floor vibration constitutes a disturbance to people, it is desirable to establish whether that level can be perceived. At present there is no sociological data relating the degrees of human sensitivity to traffic vibration with the level of vibration. However it is possible to compare floor vibration levels with the perception levels obtained from these studies.

2.2 Social surveys

A National Survey of traffic nuisance was carried out on behalf of the Department of the Environment in 19721.

For this survey a range of sites representative of all types of residential areas throughout England was chosen for study. The survey was designed so that data obtained from it could be used to evaluate the degree of annoyance created by various traffic effects and to determine the extent to which they constituted a national problem.

About ten per cent of all those interviewed claimed to experience vibration often and a further 26 per cent to experience it occasionally. Of those experiencing vibration often, more than half reported that vibration bothered them quite a lot or very much. This finding supports the contention that when traffic vibration is perceived it is likely to be a serious source of bother.
Further analysis revealed that traffic vibration was experienced more often by those people living near to heavily trafficked roads. For vehicle flows greater than 10,000 vehicles/day over 40 per cent of respondents experienced vibration often and about 30 per cent of respondents were bothered by the vibration. For vehicle flows less than 1,500 vehicles/day only seven per cent of respondents experienced vibration often and five per cent were bothered by the vibration.

A number of more recent studies have been carried out by TRRL in order to assess the environmental effects of traffic on the communities through which it passes. Among these effects was the disturbance felt by people in buildings due to traffic vibration.

Questionnaire surveys have been employed to determine the public’s opinions in the towns of Ludlow, Lewes and Stafford (unpublished data). Table 1 lists data obtained in these surveys, and compares the degree to which people were bothered by vibration in buildings at the three towns with that experienced in the National Survey.

Clearly the degree of bother was much greater at these three towns than the average in the National Survey.

TABLE 1
Degree to which people were bothered by vibration (%)

<table>
<thead>
<tr>
<th>Bothers</th>
<th>LUDLOW</th>
<th>LEWES</th>
<th>STAFFORD*</th>
<th>NATIONAL SURVEY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shop workers</td>
<td>Residents</td>
<td>Shop workers</td>
<td>Residents</td>
</tr>
<tr>
<td>Very much</td>
<td>50</td>
<td>33</td>
<td>29</td>
<td>28</td>
</tr>
<tr>
<td>Quite a lot</td>
<td>15</td>
<td>22</td>
<td>24</td>
<td>35</td>
</tr>
<tr>
<td>Not very much</td>
<td>25</td>
<td>27</td>
<td>35</td>
<td>28</td>
</tr>
<tr>
<td>Not at all</td>
<td>10</td>
<td>18</td>
<td>12</td>
<td>9</td>
</tr>
</tbody>
</table>

* No residential properties in the area surveyed.

3. EXPERIMENTAL MEASUREMENTS

3.1 General
The measurement sites were selected from properties located alongside the A49 in Ludlow, the A27 in Lewes, the A34 in Stafford and the A3 Guildford bypass. These locations were chosen because at Ludlow, Lewes and Stafford the results from the questionnaire surveys had shown a high degree of bother with traffic vibration. At Guildford the A3 was a heavily trafficked road where a high degree of bother with traffic vibration was expected.

At all sites there were no discontinuities in the road surface, so that ground-borne vibrations were not significant.

3.2 Description of sites
Ludlow is an historic market town lying on the A49 trunk road. This road is very narrow in the town centre, where it reaches the top of a steep hill whose average gradient is about 10 per cent. These road features create a bottleneck for traffic and congested traffic flow conditions exist for much of the time. A building near the crest of the hill in Ludlow was chosen for the measurement survey.
Lewes is a county town, through which the A27 trunk road forms a major route. This road traverses a steep hill, whose average gradient is about 10 per cent, and is bounded by a number of historic buildings which lie very close to the road. A building close to a traffic-signal controlled section of the main road was chosen for the survey. This building was adjacent to part of the hill where the gradient was about 4 per cent.

Stafford is also a county town, through which the A34 trunk road forms the major route. This road is the main shopping street in the town, and until the recently built inner ring road was opened, it was subject to congestion at pedestrian crossing points and at traffic signals. The measurement survey was in a building adjacent to a Pelican crossing, and was carried out before the ring road was opened.

The site in Guildford was adjacent to the Guildford bypass (A3). This is a two lane dual carriageway trunk road with a traffic volume greater than 30,000 vehicles/day. The site chosen for study was near to a junction on the bypass where traffic signals caused interruption to the free-flow of traffic.

Table 2 lists details of the buildings used and the road and traffic features at each site. Figure 1 shows side elevations of the buildings, and the locations of the measurement positions. Plates 1–4 illustrate the locations of the buildings at each town.

**TABLE 2**

Measurement sites in urban areas

<table>
<thead>
<tr>
<th>Location</th>
<th>Building type</th>
<th>Road features</th>
<th>Traffic* Flow</th>
<th>% HGV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ludlow town centre</td>
<td>3 storey terraced building</td>
<td>Traffic congestion due to steep gradient and narrow streets.</td>
<td>850</td>
<td>19</td>
</tr>
<tr>
<td>(A49)</td>
<td>3 m from kerb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lewes town centre</td>
<td>2 storey detached house</td>
<td>4% gradient, traffic congestion at signals</td>
<td>1,200</td>
<td>14</td>
</tr>
<tr>
<td>(A27)</td>
<td>4 m from kerb</td>
<td>100 m from building</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stafford town centre</td>
<td>2 storey end of terrace</td>
<td>Traffic congestion at Pelican crossing outside building.</td>
<td>750</td>
<td>22</td>
</tr>
<tr>
<td>(A34)</td>
<td>office building</td>
<td>Road 8 m wide.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 m from kerb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guildford bypass</td>
<td>2 storey semi-detached</td>
<td>2 lane dual carriageway; 18 m wide, traffic congestion</td>
<td>2,400</td>
<td>13</td>
</tr>
<tr>
<td>(A3)</td>
<td>house</td>
<td>due to signals. 80 m from building.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 m from kerb</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Traffic counts made during each measurement period, and averaged to give hourly flow and % HGV.

3.3 *Measurement and analysis techniques*

A standard method of measurement and analysis was employed to measure the low frequency sound pressure and floor acceleration levels in buildings. The methods used have been described in detail in previous work and this section presents these techniques only briefly.
Condenser microphones were used to monitor sound pressure levels both outside and inside each building. The outside microphone was located 1 m from the facade, 3 m above ground level. The inside microphone was located 1.4 m above the floor of a first floor room, and 1 m from the rear wall, 1 m from a side wall.

At all sites, piezoelectric accelerometers were used to monitor the first floor vibration levels. The accelerometers were attached directly to the floorboards in the geometric centre of the room, and produced an output signal proportional to the floor acceleration.

Data signals from each transducer were first amplified and then recorded simultaneously on a magnetic tape recorder which had a linear frequency response from DC up to 625 Hz. At each site several recordings were made, of duration between 20' and 60 minutes, over the time period from 8am to 8pm, in order to monitor the sound pressure and floor acceleration levels during the daytime traffic flow.

Traffic counts, with the vehicles classed as heavy or light, were taken during each measurement period. The average hourly traffic flow and percentage of heavy goods vehicles at each site is given in Table 2.

Analysis of the recorded data signals was carried out using a real time analyser to filter the signals into 1/3 octave bands. A speed transformation of the recording was used on replay to extend the analysis frequency range down to 3.15 Hz.

Two types of analysis were carried out:

1) single vehicle peak event levels, calculated during the drive-by of a vehicle. The frequency spectrum over the period, usually 1 s, corresponding to the time when the vehicle was immediately outside the building was obtained.

2) long-term statistical averages, calculated over each recording period. The distribution of instantaneous 1/3 octave levels was determined and presented as exceedance levels by calculation on a small computer directly connected to the analyser. These were the levels exceeded for one per cent, five per cent, ten per cent and fifty per cent of the analysis period. In addition, the energy-equivalent continuous level was also calculated. This is the notional sound or vibration level which, over a given time period, would result in the same amount of sound or vibration energy being measured as that due to the actual sound or vibration over the same period.

4. RESULTS OF MEASUREMENTS

4.1 Excitation of floor vibration by low frequency vehicle noise

In order to establish that low frequency sound generated by vehicles was responsible for the floor vibrations it is necessary to examine the peak sound and vibrations signals produced by individual vehicles, and to show that a direct relation exists between the sound pressure and the floor vibration.

Signals from vehicles which generated high levels of sound pressure below 100 Hz were chosen, and in practice this meant that heavy commercial vehicles or public service vehicles were the only sound sources to be considered.
One example of this is shown in Figure 2, in which the signals produced at the Ludlow site by a 32t commercial vehicle are plotted. At the time that the vehicle was immediately opposite the building, high levels of both sound pressure and floor vibration were recorded, which suggested that there was a close relation between the sound field and the floor vibration.

A further analysis of these peak signals was carried out to determine the frequency spectra. The portion of each signal which was chosen for the frequency analysis is indicated on the records.

Figure 3 shows the spectra obtained for frequencies between 3.15 and 500 Hz. It can be seen that there was a close correspondence between the outside and inside sound pressure spectra. The difference between them was determined by the frequency-dependent sound transmission properties of the building facade, i.e. that high frequencies were attenuated more than low frequencies. There was also a close correspondence between the sound pressure spectrum inside the building and the floor vibration spectrum. This can be seen from the maximum sound pressures in the 63–80 Hz bands which are reproduced as maximum floor vibrations.

Also shown on Figure 3 is the ISO threshold of perception\(^5\). This is the average curve obtained from laboratory studies of human sensitivity to continuous sinusoidal vibrations. It is clear from this spectrum that the floor vibrations at 16 and 20 Hz induced by the vehicle were greater than this threshold level.

The actual floor response to the incident sound pressure is dependent, amongst other factors, on the sound absorbing properties of the room and its furnishings and on the dynamic characteristics of the floor construction. It is likely that different buildings exposed to the same outside sound pressure spectra at the same site would respond differently to the acoustic excitation. Nevertheless, it is apparent that the mechanism by which the floor vibrations at Ludlow were induced was air-borne low frequency sound.

An examination of the vibration and sound pressure signals from individual vehicles at the other three sites also indicated that the mechanism by which the floor vibrations were induced was low frequency sound.

4.2 Long-term statistical averages

The long-term statistical averages calculated over each recording period are considered in this section. The distributions of instantaneous 1/3 octave levels are shown in Figures 4–7 for the upper floor vibrations and outside sound pressure levels at Ludlow, Lewes, Stafford and Guildford respectively.

All sites exhibited two regions of peak vibration levels. These were in the 10 to 25 Hz region and in the 63 to 125 Hz region. The peak sound pressure levels were in the 50 to 100 Hz region. Thus the floor vibration peaks at the higher frequencies corresponded to the sound pressure peaks, and can be attributed to a direct response to acoustic excitation. The origin of these sound pressure peak levels at 50 to 100 Hz is exhaust noise emission\(^8\).

At the lower frequency region, between 10 and 25 Hz, there was no obvious acoustic excitation. However, the natural frequencies of the upper floors at each site were in this frequency range. It appears, therefore, that the floor response to acoustic excitation is a mixture of free vibration at its natural frequency and forced vibration at the main excitation frequency.
It can be seen that the ISO threshold of vibration perception was exceeded for about one per cent of the time at Ludlow and Guildford. The frequencies at which the threshold was exceeded were in the range 16 to 20 Hz. At the other sites the one per cent exceedance levels were not above the perception threshold.

5. DISCUSSION

The results of measurements of structural vibration and low frequency traffic noise given in this report were obtained at four sites chosen to be representative of urban areas and congested traffic conditions. The sites were located alongside roads with smooth surfaces so that ground vibrations originating in the road surface were well below perceptible levels.

As expected it was found that the floor vibrations in the test houses were primarily caused by acoustic excitation at frequencies below 100 Hz. The magnitudes of the floor vibrations were compared with the perception thresholds given in the draft ISO standard. It was found that the floor vibrations exceeded the perception threshold for only one per cent of the time and at only two of the sites. At the other two sites the perception threshold was not exceeded at the one per cent level. Nevertheless a high degree of bother with vibration had previously been reported at three of the test sites where between 30 and 65 per cent of those interviewed claimed to be either 'quite a lot' or 'very much' bothered by vibration from traffic. It would appear, therefore, that the one per cent exceedance vibration levels recorded at the sites are not a suitable measure of vibration disturbance. It should be noted, however, that the perception limits proposed by ISO and compared with this data represent an average of a number of different experiments and, consequently, there is a considerable scatter on the results used to define the standards proposed. Furthermore, the perception limits are based on laboratory experiments in which subjects were exposed to continuous vibrations and, therefore, may not be appropriate to subjects exposed to the fluctuating and complex vibrations caused by road traffic. However, despite the uncertainty in applying the ISO vibration thresholds to determine whether traffic induced structural vibrations are perceptible it seems more likely that vibration bother results from a more complicated mechanism involving both body vibrations and auditory effects.

Body vibrations are caused by air pressure changes acting uniformly over the whole body surface. Resonances of parts of the body can be induced at certain frequencies when the sound pressure levels are sufficiently high. Experiments have shown that chest resonances are the most marked and occur at frequencies around 50 Hz in male subjects9.

Auditory sensations which may be described as 'vibration' sensations occur in response to low frequency sounds at frequencies below 100 Hz, and can give rise to a considerable degree of annoyance at relatively low exposure levels10,11.

Clearly, low frequency sound can cause both body and auditory vibration sensations which can give rise to disturbance. At the four test sites low frequency sound was also responsible for the floor vibrations which were probably perceptible for short periods. It is suggested, therefore, that the physical parameters used to relate vibration bother with vibration level should be based on measurements of low frequency traffic noise.
6. CONCLUSIONS

The following conclusions may be drawn from this study:

1. At four sites where social surveys had shown that there was a high degree of bother with traffic vibrations and where ground vibrations were not significant, air-borne low frequency noise was responsible for floor vibrations in buildings.

2. Since the floor vibrations were above the ISO vibration perception thresholds for only one per cent of the time and at only two of the four sites, the floor vibration level is not a suitable measure of vibration bother.

3. It is suggested that the physical parameters used to relate vibration level with vibration bother should be based on measurements of low frequency traffic noise.

7. ACKNOWLEDGEMENTS

The work described in this Report was carried out in the Environment Division (Division Head: Mr L H Watkins) of the Transport Systems Department of TRRL.

Assistance in the measurement and analysis of data was given by Mr D A Snashall who attended the Laboratory for 6 months of industrial training from the University of Bath.

The frequency analyses were carried out in cooperation with Mr R C Hill of the Scientific Branch, the Greater London Council.

8. REFERENCES


Fig. 2 SOUND PRESSURE AND VIBRATION LEVELS DURING PASSAGE OF 32t COMMERCIAL VEHICLE AT LUDLOW

(a) SOUND PRESSURE OUTSIDE FRONT FACADE

(b) SOUND PRESSURE INSIDE UPPER FLOOR ROOM

(c) VIBRATION OF UPPER FLOOR

* Vehicle immediately opposite the building
Fig. 3 SOUND PRESSURE AND VIBRATION SPECTRA DURING PASSAGE OF 32t COMMERCIAL VEHICLE AT LUDLOW
Fig. 4 VARIOUS EXCEEDANCE LEVELS AT LUDLOW FOR PERIOD 09.00 TO 09.40 (Vehicle flow 850/h)
Fig. 5  VARIOUS EXCEEDANCE LEVELS AT LEWES FOR PERIOD 08.40 TO 09.20 (Vehicle flow 1200/h)
Fig. 6 VARIOUS EXCEEDANCE LEVELS AT STAFFORD FOR PERIOD 13.30 to 14.10 (Vehicle flow 750/h)
Fig. 7 VARIOUS EXCEEDANCE LEVELS AT GUILDFORD FOR PERIOD 11.30 to 12.30 (Vehicle flow 2400/h)
Plate 1 LUDLOW TOWN CENTRE

Plate 2 LEWES HIGH STREET
Plate 3 STAFFORD HIGH STREET

Plate 4 GUILDFORD BYPASS
ABSTRACT

LOW FREQUENCY TRAFFIC NOISE AND BUILDING VIBRATION: D J Martin BSc PhD MInst P. Department of the Environment Department of Transport, TRRL Supplementary Report 429: Crowthorne, 1978 (Transport and Road Research Laboratory). Building vibrations caused by heavy traffic close to buildings in urban areas were investigated at four sites where a high degree of vibration bother had been demonstrated or was expected. It was found that low frequency acoustic excitation was responsible for floor vibrations at all sites. Floor vibrations were generated in two frequency ranges. These were at 63 — 125 Hz which corresponded with the excitation frequencies of exhaust emissions, and at 10 to 25 Hz which corresponded with the natural frequencies of the upper freely-suspended floors at the sites. The use of vibration perception thresholds to describe criteria for bother is discussed. It is suggested that the mechanism of vibration disturbance may be a complex combination involving structural vibration and low frequency sound which may be either heard or felt as body vibration.

ISSN 0305-1315