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# Ground-borne vibration generated by vehicles crossing road humps and speed control cushions

G.R. Watts[a,*], V.V. Krylov[b]

[a]Noise and Vibration Group, Transport Research Laboratory, Old Wokingham Road,
Crowthorne, Berkshire, RG45 6AU, UK
[b]Nottingham Trent University, Nottingham, UK

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## Abstract

Road humps and speed cushions are used to control vehicle speeds in residential areas. Ground-borne vibrations are produced when vehicles pass over these profiles and in some cases they can reach perceptible levels in adjacent buildings. This paper describes a study to assess the size and nature of these vibrations. Measurements of peak particle velocity have been taken alongside a selection of hump and cushion designs using a range of vehicles under controlled driving conditions. Vibration levels have been predicted using a vehicle model and related to measured values. Results from a previous study of the generation and transmission of traffic vibration in different soils have been used to provide guidance on the siting of these surface profiles to avoid disturbance. The research highlights the need to carefully consider the siting of these profiles especially on soft soils. © 2000 Transport Research Laboratory. Published by Elsevier Science Ltd. All rights reserved.

*Keywords:* Traffic-induced vibration; Road humps and speed cushions; Perception of vibration

## 1. Introduction

Road humps are commonly used by Local Authorities in the UK at sensitive road locations as a means of reducing vehicle speeds and hence accidents. Speed cushions, a form of road hump, only span part of the carriageway width and are designed to reduce light vehicle speeds but allow larger vehicles with wider wheel tracks to straddle all or most of the raised area. This reduces passenger discomfort in buses and allows large emergency vehicles to use routes where cushions have been installed with relatively little restriction.

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* Corresponding author. Tel.: +44-(0)1344-770-414; fax: +44-(0)1344-770-918.
*E-mail address:* grwatts@trl.co.uk (G.R. Watts).

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Early studies were concerned with designing humps to cause uncomfortable vibrations *inside* the vehicle when the design speed was exceeded [1] but little consideration was given at that time to the vibrations generated in the ground. However, more recently concern has been expressed by some Local Authorities about the level of ground vibrations experienced by residents living close to affected roads. Some residents groups report severe disturbance including sleep disturbance and property damage.

This Paper describes a study to assess the vibration levels generated by a wide range of vehicle types crossing a selection of hump and cushion designs. Measurement of peak particle velocity (PPV) has been taken on a test track close to each profile and comparisons have been made with predictions obtained from a vehicle model. Using results from a previous study of the generation and transmission of traffic vibrations in different soils [2] the maximum likely levels of vehicle generated ground-borne vibration alongside each profile design have been predicted for a range of site conditions. This information can be referred to by Local Authorities when selecting traffic calming measures to ensure that residents are not exposed to levels of vibration likely to cause disturbance.

## 2. Theory

Ground-borne vibrations are generally perceptible in situations where the road surface is uneven and buildings are situated close to the road [3]. Road humps and cushions can therefore be a potential source of this type of vibration. The frequencies of these vibrations are generally in the range 8–16 Hz and result from the "wheel hop" mode of vibration of the vehicle's suspension, i.e. the oscillation of the axle and wheel between the tyre and suspension. Both compression and shear waves are produced in the ground and their amplitudes and attenuation with distance depend critically on the soil composition. These short duration or impulsive ground-borne vibrations, rather than those produced by airborne sound waves, often produce the highest peak particle velocities (PPVs) in the hard structure of the building. Previous research has examined the effects of traffic-induced ground-borne vibrations on buildings and soils [3].

For small irregularities in the road surface an empirical prediction equation has been developed based on measurements on a wide variety of soils and from TRL test track experiments [2]. This predicts the expected maximum vertical velocity in mm/s, $PPV_{\max}$, at a building foundation due to heavy vehicles passing over a road surface defect. The $PPV_{\max}$ is given by:

$$PPV_{\max} = 0.028agp\frac{v}{48}\left(\frac{r}{6}\right)^{x} \tag{1}$$

where $a$ = maximum height or depth of the road surface defect in mm, $v$ = maximum expected speed of HGVs in km/h and $g$ = ground scaling factor (explained below). If the surface defect occurs in one wheel path then $p = 0.75$, otherwise $p = 1$. The distance of the measurement point from the defect in metres is $r$ and $x$ is the power coefficient, which determines the rate of attenuation in different soil types.

Although it would be possible to use this equation to estimate the maximum vibration generated by heavy vehicles passing over a road hump it should be noted that the equation was developed from results where vehicles travelled over relatively small discontinuities in the road surface (i.e. maximum lengths and heights were 1.2 m and 55 mm, respectively). Typically road humps present a significantly larger road profile with lengths ranging over 8 m and heights up to 100 mm. Consequently, it was not considered valid to extrapolate results in order to predict the effects of the introduction of these devices. The experimental design used in the present study was to measure the vibration levels produced by a wide range of vehicles crossing a range of different humps and cushions under controlled conditions on the TRL test track and then to estimate effects at different sites by taking into account the generation and propagation of vibration in different soils.

Previous studies have established that the shear modulus of the ground is an important determinant of the level of the vibration produced by a given size of irregularity. Where the shear modulus is low, e.g. in soft soils such as alluvium and peat deposits, a relatively large response can be expected while material with a high modulus such as rock, little vibration is generated. It is therefore essential to make corrections for ground conditions when extrapolating from measurements taken, for example, on the TRL test track where the underlying subsoil is relatively firm, to other sites where the soil conditions are significantly different. This adjustment has been 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. The PPV at a site, $PPV_s$, can be calculated from:

$$PPV_s = PPV_t \frac{H_s(f)}{H_t(f)}$$

where $PPV_t$ is the peak particle velocity measured on the test track and $H_s(f)$ and $H_t(f)$ are the moduli of the transfer functions at the site and on the track respectively and $f$ is the forcing frequency. In this case the transfer function $H(f)$ is defined as the ratio of the amplitudes of the vertical velocity at a given distance resulting from the application of a vertical sinusoidal force of frequency $f$ at the origin. For the purposes of this study and previous work the forcing frequency has been taken to be 12 Hz as this is a typical wheel hop frequency. The factor $H_s(f)/H_t(f)$ is referred to as the ground scaling factor, $t$, in Eq. (1) above. Values of $t$ based on measurements carried out at the track location where the humps were tested have been found to range from 0.06 for very firm ground such as chalk rock to 4.40 for a soft soil such as alluvium.

## 3. Vehicle model

Theoretical investigations of ground vibrations generated by road traffic on statistically rough surfaces and by accelerating and braking vehicles have been carried out by several authors [4–8]. However, vibrations caused by vehicles travelling over single obstacles such as road humps have received attention only recently [9].

Typical mechanical models of a two axle road vehicle travelling on uneven road surface possess four degrees of freedom corresponding to four main low frequency resonances related to body bounce and pitch and front and rear wheel hops [6,9,10]. Body bounce and pitch resonances are normally in the range 1–3 Hz and do not lead to appreciable ground vibrations. This is evident from records of vibration time histories of heavy vehicles crossing road irregularities. Generally, for these conditions wheel hop frequencies dominate, with the heaviest axle of a two axle vehicle generally producing the highest vibration levels [3]. Consequently, in order to predict the PPV from two-axle heavy vehicles passing over a hump, a simple one-axle model was used. This contrasts with a two-axle model considered previously [9].

The model adopted takes into account only vertical vibration of the wheel and axle assembly and for this purpose the body is immobile. Fig. 1 illustrates the modelling concepts where the wheel-axle mass is $m$ and $K_1$ and $K_2$ are the spring constants of the tyre and suspension respectively. If the hump cross-section is described by the function $z_1 = f(x)$ where $x$ is the horizontal dimension, then the equation describing vertical displacements of the axle $z_2$ is then given by:

$$m\frac{\partial^2 z_2}{\partial t^2} + Q\frac{\partial z_2}{\partial t} + Kz_2 = K_1 z_1(t) \tag{2}$$

where $K$ is the combined elasticity of tyre and suspension $(K_1 + K_2)$ and $Q$ is the total damping coefficient.

Solving Eq. (2) by the Fourier method the Fourier transform $Z_2(\omega)$ of the wheel-axle displacement $z_2(t)$ is:

$$Z_2(\omega) = \frac{\omega_1^2 Z_1(\omega)}{\sqrt{(\omega_0^2 - \omega^2)^2 + (2\omega\alpha)^2}} \exp\left(-i\tan^{-1}\left(\frac{2\omega\alpha}{\omega_0^2 - \omega^2}\right)\right) \tag{3}$$

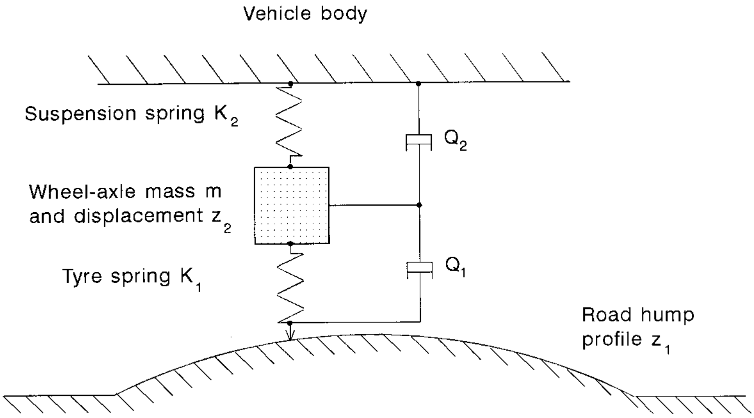

Fig. 1. Simplified mechanical model of a vehicle taking into account only wheel-axle vibrations.

where $\omega_0 = \sqrt{(K/m)}$ is the wheel hop frequency, $\omega_1 = \sqrt{(K_1/m)}$ is the natural frequency of oscillation of the wheel-axle assembly on the tyre, $\alpha = Q = 2m$ is the normalised damping coefficient and $Z_1(\omega)$ is the Fourier spectrum corresponding to the hump profile.

The Fourier spectrum of the force applied to the road during the pass-by is then:

$$T(\omega) = K_1(Z_2(\omega) - Z_1(\omega)) \tag{4}$$

This force is responsible for generating ground vibrations, which were calculated using the Green's function formalism developed in a previous paper [9]. Integration of generated ground vibration spectra around the dominant frequency $\omega_0$ was used to obtain the PPV.

The vehicle model was initially calibrated for the case of a two-axle vehicle traversing a single hump and then the model was used to predict PPVs under further conditions.

## 4. Experimental method

### 4.1. Test profiles

A total of eight profiles were selected for the study and the dimensions are given in Table 1. The specifications were representative of designs which are in common use on the public highway. The wide cushions (A, B and C) had an overall width (OW) of 1900 mm and widths of the raised area (plateau widths, PW) that would enable most heavy vehicles to track along the sloped sides of the profiles. OL and PL are

Table 1
Dimensions of test profiles

| Profile code | Dimensions (mm)[a] | | | | | Gradients | |
|---|---|---|---|---|---|---|---|
| | OL | OW | PL | PW | H | Ramp | Side |
| *Cushions* | | | | | | | |
| A | 2000 | 1900 | 800 | 1300 | 74 | 1 in 8.1 | 1 in 4.1 |
| B | 3500 | 1900 | 2300 | 1300 | 71 | 1 in 8.5 | 1 in 4.2 |
| C | 3500 | 1900 | 2540 | 1420 | 72 | 1 in 7.7 | 1 in 3.3 |
| D | 3500 | 1600 | 2540 | 1120 | 64 | 1 in 7.5 | 1 in 3.8 |
| E | 3500 | 1500 | 2540 | 1020 | 65 | 1 in 7.4 | 1 in 3.7 |
| *Humps* | | | | | | | |
| F | 7800 | 4000 | 6000 | 3400 | 73 | 1 in 12.3 | 1 in 4.1 |
| G | Round-top profile hump 64 mm high, 3700 mm long, 3400 mm wide with tapered sides with overall width 4000 mm. | | | | | | |
| H | Round-top profile hump 74mm high 900mm long, 3400 mm wide with tapered sides with overall width 4000 mm. | | | | | | |

[a] OL, overall length; OW, overall width; PL, plateau length; PW, plateau width; H, mean height.

overall length and plateau length, respectively. Most light vehicles, having a narrower wheel track, would be elevated to the full height of the plateau. The narrow cushions (D and E) would almost be completely straddled by heavy vehicles. The narrow cushions also had lower mean plateau heights than the wide cushions. The on/off ramp gradients and side gradients are given in Table 1. Profile G was a round-top hump 3700 mm long, 64 mm high, with gradual gradients. In contrast, profile H was a round-top design, only 900 mm long, and 74 mm high, forming steep on/off gradients. Profile F represented a long flat-top design, 73 mm high, with approximately 1:12 ramp gradients at each end. The overall length was nearly 8 m.

These test profiles were constructed on the TRL test track using a dense bituminous macadam material commonly used as a road surfacing in urban areas.

### *4.2. Vehicle selection and operation*

Eleven vehicles were selected: one light vehicle, three buses and seven commercial vehicles. The selected vehicles had a range of different characteristics that might affect vibration generation such as vehicle weight, axle configuration and suspension type (see Table 2). With this wide selection of vehicles it was reasoned that likely maximum levels of roadside vibration would be determined for the range of profiles tested. Gross vehicle weights (GVWs) in the sample ranged from 1.7 t to approximately 38 t. As road humps are often installed on urban routes used by buses, three typical designs of bus were included. Commercial vehicles included two types of two-axle rigid trucks of 7.5 and 17 t GVW, respectively, two articulated trucks with a GVW of 38 and 32.5 t, respectively, and trucks with steel leaf and air suspensions. Most of the commercial vehicles were tested in both laden and unladen conditions.

For each test vehicle, drive-by tests were carried out over at least six of the eight test profiles. Supplementary tests were performed with the vehicles crossing two of the cushion profiles (B and E) off-centre, that is, with the nearside wheels crossing the plateau of the cushion and the off-side wheels tracking along the level road surface to

Table 2
Details of vehicles used during the study

| Vehicle no. | Description | Model | Suspension type | Weight during tests (tonnes) |
|---|---|---|---|---|
| 1 | Passenger car | Ford Sierra 1.8D | Coil | 1.4 |
| 2 | Dropside truck | M.A.N. | Steel | 7.4 |
| 3 | Single deck bus | Optare Delta | Air | 10.1 |
| 4 | Double deck bus | Optare Spectra | Air | 11.4 |
| 5 | Midi bus 25 seats | Optare Metrorider | Steel | 5.3 |
| 6 | Dropside rigid truck | Renault Dodge | Steel | 6.9 |
| 7 | Vehicle 6 (laden) | Renault Dodge | Steel | 16.1 |
| 8 | Tractor and tipper trailer | Mercedes | Steel | 13.6 |
| 9 | Vehicle 8 (laden) | Mercedes | Steel | 38.4 |
| 10 | Tractor and trailer | DAF95 350 ATI (Leyland) | Air | 17.4 |
| 11 | Vehicle 10 (laden) | DAF95 350 ATI (Leyland) | Air | 32.2 |

one side. Specifically, on the approach to the test cushion the vehicle was aligned such that the nearside wheel tracked across the profile halfway between the centre-line and the nearside edge of the plateau. This type of driving operation may perhaps be adopted by a driver if the approach to a cushion is partially obstructed by a vehicle parked at the side of the road. For the purposes of this study this test condition will be described as 'not-straddling'. All other drive-bys were carried out with the vehicle aligned centrally with the test profile ('straddling').

Drive-bys were performed at road speeds of 15, 25, 35 and 45 km/h. It was known from previous surveys that this range of speeds would encompass typical crossing speeds recorded on the public highway [11].

### 4.3. Vibration measurement

Fig. 2 shows the layout of the test site. An array of three geophones was mounted firmly on the surface of the test track alongside the test profile to detect vibrations along three orthogonal axes (vertical, radial and transverse). The mounting position was in line with the centre of the profile at a distance of 6 m from the nearside wheel track.

The geophones were connected to a multi-channel signal processor, which digitised the input signals at a sampling rate of 1 kHz. This device was connected to a portable computer, which scaled and recorded the digitised particle velocity signal. Following each drive-by, the maximum velocity amplitude (PPV) value in each axis was recorded. Vehicle road speed was monitored using a radar speed meter. At least two measurements were taken for each drive-by condition.

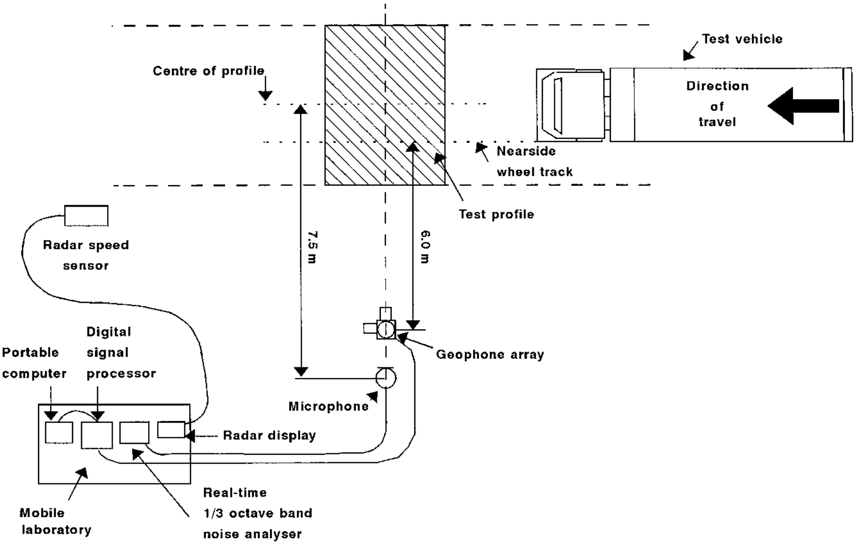

Fig. 2. Layout of test site and measurement equipment.

## 5. Results

Typically peak vibration levels in the radial and transverse direction were less than 0.1 mm/s and in comparison with the vertical levels recorded under similar conditions were not considered significant. Consequently, only the peak vibration amplitudes in the vertical direction were considered for further analysis.

### *5.1. Ground-borne vibration levels and vehicle speed*

Generally the highest levels of vibration were produced by the heaviest vehicles. Considering all profiles the maximum and mean PPVs for vehicles over 7.5 tonne were 0.51 and 0.25 mm/s, respectively, while for vehicles less than 7.5 tonne the corresponding levels were 0.23 and 0.1 mm/s.

Fig. 3(a) shows the PPV values recorded versus speed relationships for the heaviest two axle vehicle (vehicle 7) and Fig. 3(b) shows the trends for the heaviest articulated vehicle (vehicle 11). As noted in previous studies there is a tendency for vehicle generated vibration to increase with increases in drive-by speeds for all of the profile designs tested. This effect is most pronounced for profile H (narrow round top hump) which caused the test vehicles to generate the highest levels of vibration recorded during the study. Profile F, the long flat-top hump produced higher levels than the long round top profile G. Profiles D and E, the narrow cushions, gave results which were similar to each other and gave the lowest vibration levels relative to the other profiles. Fig. 4 shows the vertical particle velocity time history recorded when vehicle 7 crossed profile F at 45 km/h. The average wheel hop frequency was approximately 12 Hz. The first peak in the time history is caused by the front axle tyres impacting the leading edge of the hump. The second and third major peaks were caused by the rear axle tyres striking the hump and then impacting the road after passing over the profile.

Fig. 5 shows for the three hump profiles (F, G and H) the predicted PPV using the vehicle model and measured PPV for the heavy two-axle vehicle 7. The vehicle model was calibrated at a speed of 25 km/h for the profile G. It was assumed that the wheel-axle assembly was 1 tonne, the wheel hop frequency was 12 Hz and natural frequency of the wheel-axle assembly on the tyre was 10.3 Hz. It can be seen that the predicted values are in reasonable agreement with the experimental data especially in the case of the round top hump G. Both measured and predicted values show a trend of increasing vibrations with speed. The predicted vibrations produced by the flat-top profile F always lie above that for the round-top profile G of similar proportions and indicate a divergence above 35 km/h. Both these tendencies are reflected in the measured data. The predicted vibrations for hump H lie above the measured levels however they indicate similar rapid increases as the measured values at the highest speeds. A likely reason for the discrepancies between predicted and measured values of PPV, especially for the shortest hump profile H, is that the effective profile is smoother than the geometric profile due to the deformation of the tyres rolling over the hump. This deformation is likely to be greatest for a short rather than a long base hump. Since the model does not account for the varying

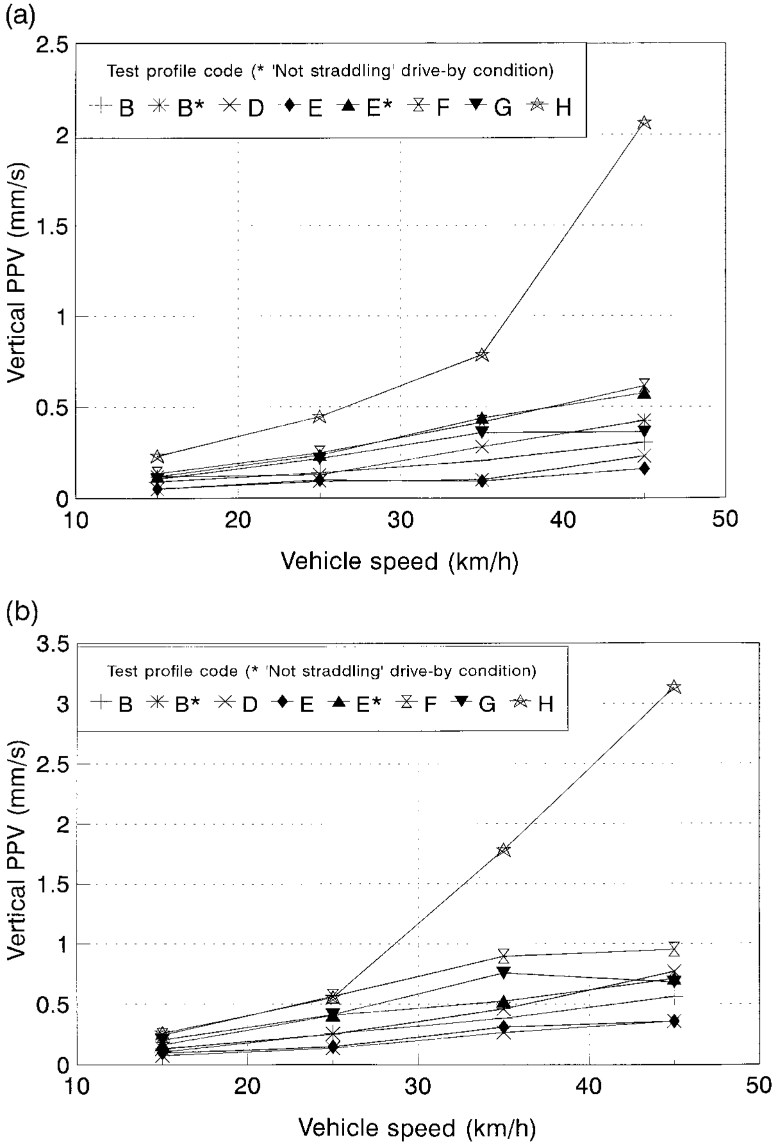

Fig. 3. Measured vertical PPV with vehicle speed for (a) vehicle 7 (heaviest two-axle truck) and (b) vehicle 11 (articulated truck).

degrees of deformation the Fourier spectra of the forces $T(\omega)$ applied to the road and the resulting predicted vibration levels are likely to be lower than the measured levels of ground vibration generated for profile H. In future modelling the effect of the size of the wheel-contact patch with the road surface should be taken into account. Other possible reasons for the discrepancies include the non-linear spring rate and variable damping of the lorry's suspension and the constraint within the

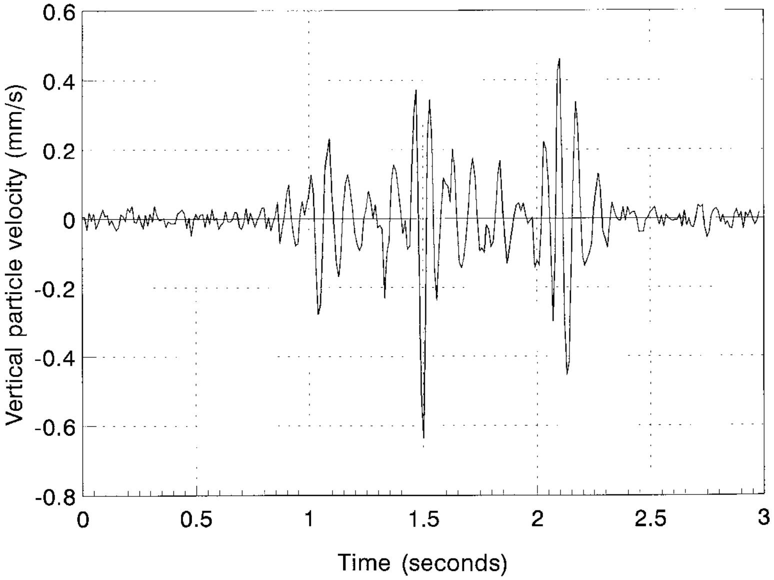

Fig. 4. Time history of vertical particle velocity for vehicle 7 (heaviest two-axle truck) over profile F at 45 km/h.

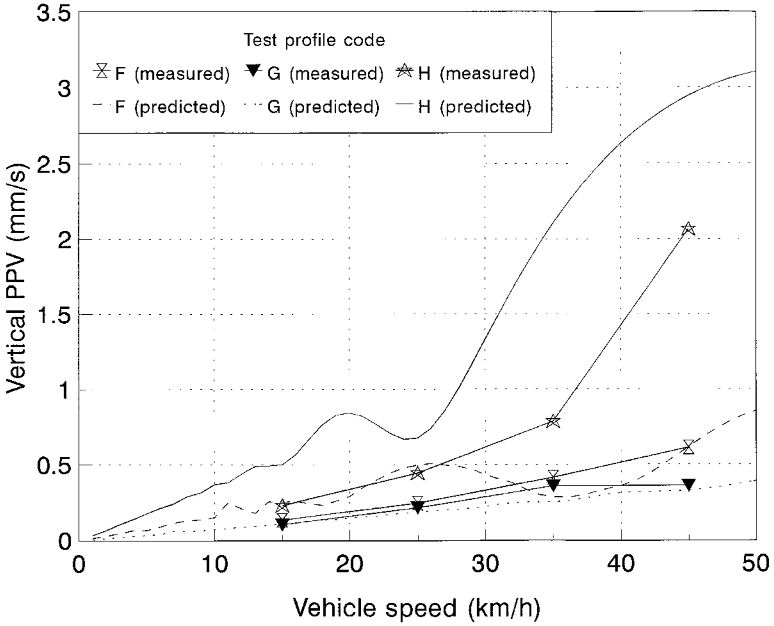

Fig. 5. Measured and predicted vertical PPV with vehicle speed for vehicle 7 (heaviest two-axle truck).

model on the movement of the vehicle body. A suitably modified vehicle model would be useful in examining a wider range of profiles than would be possible with an experimental approach. Such a further study might prove useful in identifying more appropriate profiles for speed control.

### *5.2. Comparison of ground-borne vibration levels alongside different road profiles*

Table 3 compares the calculated vibration levels alongside the different profile designs at the typical mean drive-by speed for each profile. The typical mean speeds for light and heavy vehicles were determined from survey data recorded at road sites where profile designs similar to those used in the test had been installed [11]. These results provide a more meaningful comparison of the vibration levels likely to be caused by the different profile designs in practice. It can be seen that most of the typical drive-by speeds do not coincide with the actual drive-by speeds used during this study. Consequently, where necessary, the PPV values shown in the table have been calculated by interpolating between mean PPV values at test speeds above and below the typical drive-by speed. Profiles H, B (not straddling) and E (not straddling) have been excluded from these tables as typical crossing speed data were not available for these profiles.

The data in Table 3 give an indication of which profiles cause the least vibration generation under typical conditions. For example, profile G would appear to limit light and heavy vehicle speeds as effectively as profile F, but cause lower levels of maximum and means vibration. Likewise, it is likely that drivers typically cross cushions of profile design B at the same speed as they would cross cushions of profile design C, and yet the vibration generated alongside cushion B at these speeds was less. Although the mean heights of these profiles were approximately equivalent, the side gradients of profile C were steeper. This would have the effect of causing vehicles to ride higher over the profile than was the case for profile B. The generally higher vibration levels generated alongside profile C relative to profile B can most likely be attributed to the greater vertical displacement of vehicles passing over this profile.

Table 3
Maximum and mean of PPV for all test vehicles for each profile at typical mean crossing speed

| Profile code[a] | Typical drive-by speed (km/h)[b] | | PPV (mm/s) | |
|---|---|---|---|---|
| | Light vehicle | Heavy vehicle | Maximum | Mean |
| C | 22 | 24 | 0.51 | 0.26 |
| F | 22 | 18 | 0.41 | 0.25 |
| A | 22 | 24 | 0.40 | 0.22 |
| E | 42 | 40 | 0.34 | 0.20 |
| D | 30 | 34 | 0.31 | 0.19 |
| B | 22 | 24 | 0.30 | 0.19 |
| G | 22 | 18 | 0.29 | 0.19 |

[a] In order of highest maximum vibration level.

[b] See Reference [11].

## 6. Prediction of vibration at other sites

### 6.1. Predictions for different soil conditions

Table 4 lists the ground scaling factors, $g$, and power coefficient for attenuation, $x$, (referred to in Section two, Theory) that need to be applied to the track test results, $PPV_t$, in order to predict vibration levels on different soils.

Applying these scaling factors to the results for the different profiles and modifying the prediction equation (1) above it can be seen that the predicted PPV at the building foundation at a site location, $PPV_s$, is given by:

$$PPV_s = PPV_t g\left(\frac{r}{6}\right)^x \tag{5}$$

where $r$ is the distance from the measurement point to the nearest wheel track over the profile and $x$ is the power coefficient, which determines the attenuation rate.

For each hump or cushion tested, Eq. (5) can be used to determine the closest distance, $r_{\min}$, that a profile can be positioned to a dwelling before there is a likelihood of perceptible vibrations or risk of building damage.

To avoid exceeding the criterion level in each case this minimum distance is given by:

$$r_{\min} = 6\left(\frac{PPV'_s}{PPV_t}\right)^{1/x} \tag{6}$$

where $PPV'_s$ is the criterion level for either perceptible vibrations or building damage.

The results of the calculations of minimum distances for various ground conditions are given below.

### 6.2. Criteria for disturbance and building damage

It is important to consider what guidance is available in order to determine the minimum levels of vibration that are likely to be perceptible in buildings and the minimum levels at which there is a risk of building damage.

Table 4
Ground scaling factors and power coefficients for different soils

| Ground type | Ground scaling factor ($g$) | Power coefficient for attenuation ($x$) |
|---|---|---|
| Alluvium | 4.40 | −0.79 |
| Peat | 2.39 | −1.19 |
| London clay | 1.93 | −1.06 |
| Sand/gravel | 0.58 | −0.74 |
| Boulder clay | 0.27 | −0.93 |
| Chalk rock | 0.06 | −1.08 |

It has been found that a continuous sinusoidal vibration in the vertical direction becomes perceptible at frequencies typical of traffic vibration when the PPV exceeds approximately 0.3 mm/s [12]. For short duration vibrations characteristic of traffic vibration the threshold is likely to be higher [13]. Note that British Standard 6472:1992 [14] specifies a method for determining satisfactory vibration levels of short duration or impulsive vibration in terms of measured PPV but this is most appropriate for blast induced vibrations. The threshold value represents an average value over a number of human subjects and therefore the possibility arises that some residents will detect the vibration at a lower level. Complaints are possible once vibration has been detected but a complaint threshold above which the vibration level is considered unacceptable can be considered to lie at a higher vibration level. On the available evidence it is not possible to give precise levels at building foundation level above which complaints from traffic vibration can be expected. A complicating factor is the manner in which ground-borne vibration is transmitted to the occupants. Amplification is known to occur on upper floors and the orientation of the body affects the sensitivity to vibration. However, from a review of the literature it was suggested that some degree of disturbance would probably occur when PPV levels exceed 0.3 mm/s while above 1.0 mm/s vibration levels may prove unacceptable and complaints may be made [3].

Studies of the effects of traffic vibration on buildings have indicated that there is no evidence that traffic vibration has a significant damaging effect on buildings. However, household surveys of traffic vibration have revealed that over 50% of residents considered that such vibration could cause damage [15]. Some superficial hairline plaster cracking was observed in a test house exposed to sustained repeated simulated traffic vibration with a PPV at foundation level approaching 3 mm/s [3] which is an order of magnitude higher than the perception threshold. This cracking was considered to be a result of fatigue damage since damage occurred after several weeks of continuous vibration exposure. A review of case history information and damage induced by operations such as blasting and piling has been carried out and guide threshold values for direct vibration damage have been given in BS 7385:Part 2 [16]. The threshold relates to very minor damage ('cosmetic damage') such as the formation of hairline cracks on plaster finishes or in mortar joints and the growth of existing cracks. At a typical traffic induced vibration frequency at foundation level of 12 Hz the guide PPV value of 19 mm/s lies significantly above the expected complaint level.

### 6.3. Minimum distances to nearest dwelling

The guide PPV threshold values of 0.3 mm, 1, 3 and 19 mm/s for perception, complaint, fatigue damage and damage defined in BS 7385, respectively, were used to establish minimum distances at which humps and cushions should be constructed from the nearest dwelling to avoid these consequences. Eq. (6) above was used to calculate these distances using the scaling factors and power coefficients for attenuation given in Table 4 for the six ground types ranging from soft soils (alluvium and peat) to chalk rock. For prediction purposes the maximum PPVs obtained

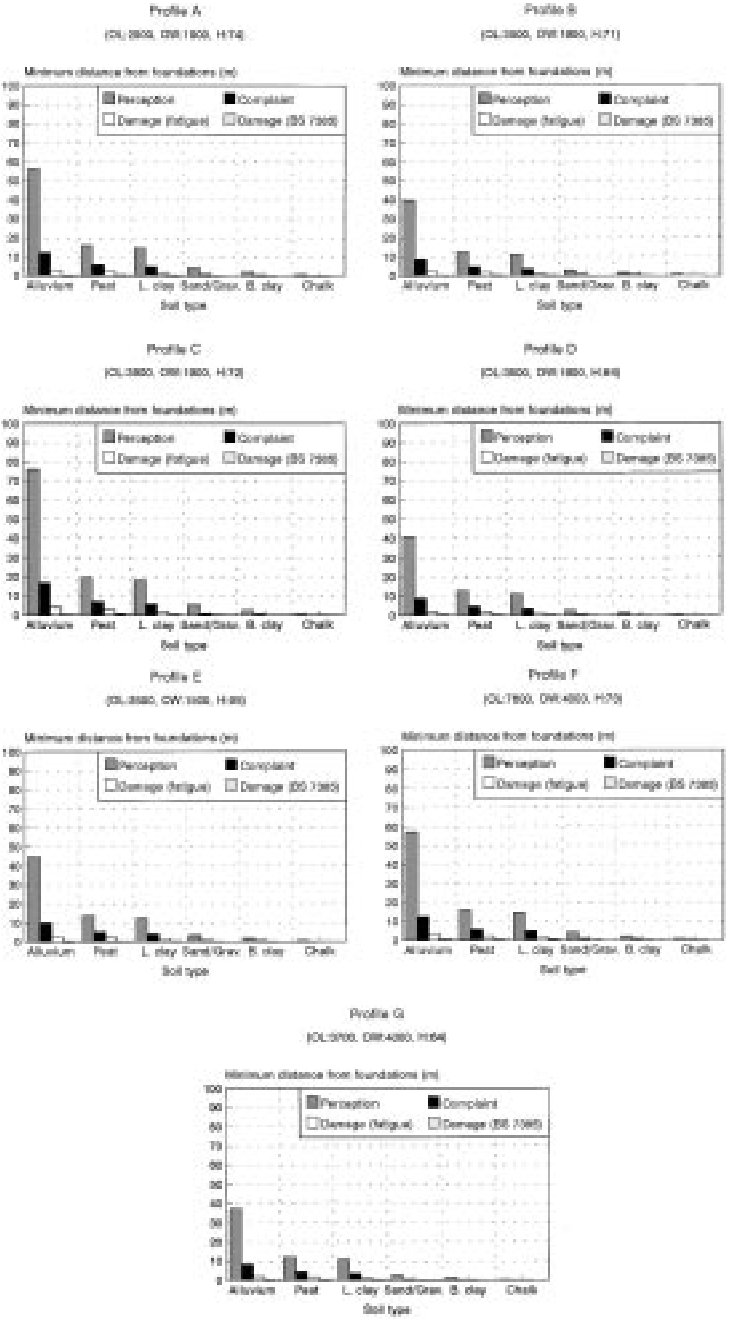

Fig. 6. Predicted minimum distances between road profiles and dwellings to avoid vibration exposure.

at the typical mean crossing speed over each profile listed in Table 3 were used. In the case of cushions, the not straddling condition [profiles B (not straddling) and E (not straddling)] do not normally occur for heavy vehicles (approximately 2% at one location in a recent survey) and consequently there is little data for average crossing speeds under this condition. For this reason predictions are not given in these cases. However, at one survey site where a cushion similar in dimensions to profile E was installed it was found that peak vibration levels were increased on average by approximately 50% when heavy vehicles clipped rather than straddled the cushion [11]. In the case of hump H there is no crossing speed data available and because of the severity of the profile it is unlikely that this hump will be used on public roads.

For each profile the minimum distances are shown in graphical form in Fig. 6. It is clear that even very minor fatigue damage is unlikely to occur unless the profiles are placed less than 4 m from the nearest foundation on soft soils. It can be seen that minimum distances for the complaint threshold range up to 17 m and for perception threshold up to 76 m. Both thresholds are for profile C on alluvium.

It is quite possible for higher levels than those predicted to be encountered in some cases especially if the soil is layered so that significant reflections occur leading to lower rates of attenuation. In addition of course the soil type may not fall neatly within the categories for which data is available. In such cases it may be necessary to carry out measurements to verify these predictions.

## 7. Conclusions

The results of this study show that speed control cushions and road humps can produce perceptible levels of ground-borne vibration. This can lead to complaints under the most severe conditions and anxieties concerning building damage. However, even under these worst case conditions it is very unlikely that the introduction of the profiles pose a significant risk of even minor damage to property.

The research has revealed the nature and scale of the problem and highlights the need to carefully consider the siting of these profiles in order to avoid causing vibration nuisance. The predictions of minimum distances between the various profiles and nearest dwelling on different soils should prove useful in avoiding problems in the future.

The vehicle model could be developed further to allow greater prediction accuracy. Such a model could prove useful in identifying promising designs which would limit the generation of ground-borne vibrations while providing appropriate levels of in cab vibration to discourage excessive speed.

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Department of the Environment, Transport and the Regions. Any views expressed in the paper are not necessarily those of the Department. Copyright TRL Limited 1999.

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