TRANSPORT RESEARCH LABORATORY

Traffic calming: Vehicle generated noise and ground-borne vibration alongside sinusoidal, round-top and flat-top road humps

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G J Harris, R E Stait, P G Abbott and G R Watts

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Executive Summary

The installation of road humps to reduce vehicle speeds has occasionally led to concerns by some Local Authorities about vehicle generated noise and ground-borne vibration reported by residents living close to the humps. Previous track trials and roadside studies by TRL have shown that the maximum levels of noise and ground-borne vibration alongside traffic calming humps depends on the profile shape as well as the type, load and speed of the vehicle crossing the profile. In the case of ground-borne vibration generation, the local soil type is also critical.

The original work on the development of speed reducing road humps carried out at TRL resulted in the specification of a circular (round-top) hump profile which has since been successfully used on roads in many countries. Since the 1980's the regulations governing the use of road humps in England and Wales have been gradually relaxed to allow greater flexibility in the shape of humps so as to include flat-top humps, raised junctions and speed cushions. The current regulations do not specify an exact hump profile providing the humps are between 25mm and 100mm in height, at least 900mm long and with no vertical face exceeding 6mm. Humps with a sinusoidal profile have been reported as being more comfortable for cyclists, and possibly also for car drivers, than other hump profiles but little information has been available as to the degree of difference between the profiles or on their impact on noise and ground-borne vibration levels.

In order to improve the advice available to local highway authorities, the Charging and Local Transport Division of DETR commissioned TRL to undertake a comparative evaluation in terms of passenger/rider discomfort, vertical acceleration, vehicle noise generation and ground-borne vibration of a number of humps with different profiles. The five profiles used in the trials included three profiles not commonly used in Great Britain: a 3.7m long hump with a sinusoidal profile, a 5m long round-top hump, and an 8m long flat-top hump with sinusoidal ramps. Two frequently used 'standard' designs were included for comparison: a 3.7m long round-top hump and an 8m long flat-top hump with straight ramps (gradient 1:13). All the humps were 75mm high and were constructed on the TRL test track.

This report gives details of the track trial at TRL and the results obtained from the measurements of noise and ground-borne vibration levels. The 'companion' TRL Report 417 (Sayer *et al*, 1999) gives details of the results of the measurements of passenger discomfort and peak vertical acceleration. The vehicles selected for the measurements of noise and vibration alongside the profiles were chosen to give potentially 'worst case' levels based on the results from the previous track studies. The selection included commercial vehicles with different suspension types (tested laden and unladen), a double decker bus and a passenger car.

Measurements of noise and ground-borne vibration were taken during drive-bys of each vehicle passing over the different hump profiles over a range of speeds. The results showed that for the double decker bus and the commercial vehicles at typical crossing speeds, the highest levels of noise and vibration were generally caused by the flat-top (straight ramp) hump. The non-standard sinusoidal designs often caused lower ground-borne vibration levels relative to the more frequently used designs. This difference was most pronounced for the case of the flat-top (sinusoidal ramp) hump. The 5m round-top hump did not show any particular advantage over the 3.7m round-top with respect to noise and vibration generation.

For the light vehicle, at typical crossing speeds, the highest A-weighted noise level was recorded alongside the 5m round-top profile. Other than this result there were generally no distinct differences with this vehicle, for either noise or vibration generation, between the results for standard and sinusoidal designs for the flat-top or round-top humps.

Noise levels generated during drive-bys over the profiles by an unladen articulated tipper vehicle with steel suspension were approximately 3 - 8 dB(A) higher than the corresponding noise levels generated alongside the profiles by an equivalent vehicle fitted with air suspension. In the laden condition the differences between the noise levels generated by the two vehicles were greater still. Both of these vehicles were noisier in the unladen condition.

For the commercial vehicles tested, it was found that the highest noise levels generally occurred alongside the flat top hump designs. Substantially higher noise levels were noted for the vehicles tested in an unladen condition than when fully loaded. These differences were less when the vehicles compared were fitted with air suspension rather than steel suspension.

Ground vibration levels generated by the light vehicle were found to be very low and close to background levels with no significant differences noted between profile designs. For the bus and commercial vehicles, the levels of ground vibration were much higher. Higher levels were also noted for the commercial vehicles running unladen than when loaded. Also higher levels were noted for the vehicles fitted with air suspension than with steel suspension. In general, the ground vibration levels generated by the commercial vehicles were higher when travelling over the flat-topped humps than when travelling over the sinusiodal and round topped designs.

The minimum distances to avoid different levels of vibration exposure have been calculated for various underlying soil types. At the level of human perception (peak vertical vibration level of 0.3mm/s) the risk of complaints would be low. Predictions of minimum distances to avoid perception of vibration ranged up to 53m for the flat-top hump with straight ramps at a site with the softest soil type. For the sinusoidal-top and round-top humps on the same soil type the predictions were just over half this distance. On firmer soils, the minimum distances

were much smaller. Minimum distances were also calculated for the higher level of 1mm/s. Above this level complaints would be expected. On this criteria minimum distances ranged up to 12m for the softest soil type. With regard to potential damage to buildings it is very unlikely that even superficial damage could be caused by the installation of humps and cushions. However, it is noted that the propagation of vibration in soils is complex and it is possible that higher levels than those predicted could occur in some situations. Consequently the minimum predicted distances should only be used for guidance purposes and in cases of doubt it is recommended that measurements are carried out with a test vehicle and temporary profile to verify these predictions. Any such measurements should only be carried out by persons skilled in vibration measurement and interpretation of the results.

Overall the results of this study indicate that the flat-topped hump designs would produce higher noise and vibration levels than the other designs in most practical situations. Consequently by avoiding these designs in future, some of the highest noise and vibration levels generated by commercial vehicles should be reduced. Such a strategy should also produce benefits on roads with relatively few heavy vehicles since even infrequent high noise levels from commercial vehicles passing over vertical deflections can cause annoyance to local residents.

1 Introduction

Vertical deflections (road humps) were developed as a speed controlling device by TRL for the Department of Transport (DOT), now the Department of Environment, Transport and the Regions (DETR). Trials using a variety of vehicles were carried out on the test track at TRL using humps of various heights and profiles (Watts, 1973). In order to evaluate the likely effects of the humps on driver behaviour, measurements were made of driver/passenger discomfort and peak vertical acceleration inside the vehicle at a range of speeds. These experiments resulted in the specification of a circular profile 'round-top' hump of 12 feet long and 4 inches high (3.7 metres and 100 mm). After the trials, this type of road hump was successfully used on the public highway (Sumner and Baguley, 1979, Baguley, 1981).

The original Highways (Road Hump) Regulations (DOT, 1983 & 1986) allowed round-top humps of 100 mm (1983) and 75 mm to 100 mm (1986) in height, and 3.7 m in length to be installed on roads in England and Wales with a speed limit of 30 mph or less. The subsequent Hump Regulations (DOT, 1990) allowed flat-top humps and round-top humps of 50 mm to 100 mm in height, and 3.7 m in length (minimum length for flat-top). Other hump profiles were not permitted under the Hump Regulations (DOT, 1990) but it was possible for local authorities to apply to DOT for special authorisation for their use (DOT, 1993).

Since 1990, when lower humps and flat-topped humps were allowed, traffic calming has become more widespread in England and Wales. Humps are an important tool for Highway Authorities because they are effective at controlling speeds, and are generally applicable to most road layouts (Webster, 1993). The degree of discomfort and subsequent speed reduction can be altered by using different hump heights and ramp gradients. When used in 20 mph zones, the reduction in average speeds (9 mph) and flows (27%) have been found to give a reduction in injury accidents of about 60 per cent (Webster & Mackie, 1996).

The installation of road humps to reduce vehicle speeds has occasionally led to concerns by some Local Authorities about vehicle generated noise and ground-borne vibration reported by residents living close to the humps. In order to provide advice to Local Authorities, the Charging and Local Transport Division, DETR commissioned TRL to examine this problem.

The study of noise and vibration issues has taken place in several stages. Initially, vehicle and traffic noise level surveys were carried out by TRL at various road sites with humps and speed cushions (Abbott, Taylor and Layfield, 1997; Abbott, Phillips and Layfield, 1995). These studies showed that, following the installation of such measures, there was a reduction in the maximum noise levels from light vehicles (passenger cars and small vans) at sites alongside and between the speed control profiles. However, the numbers of heavy vehicles (unladen weight greater than 1.5 tonnes) in the surveys were insufficient to establish the influence of the speed control measures on noise emission from this type of vehicle.

Following the field studies a further trial was carried out on the TRL test track in 1995 to measure the noise levels generated by different types of commercial vehicle passing over different designs of hump and cushion (Abbott, Tyler and Layfield, 1995; DOT, 1996a). The vehicles selected for the trial included types of commercial vehicle thought likely to produce body noise[1] when passing over the profiles. In some cases it was found that the expected decreases in vehicle drive-by noise resulting from reductions in speed were offset by the generation of body noise. The level of body noise generation varied depending on the design of profile.

A second track trial was carried out later in 1995 to investigate the influence of suspension design and payload on noise levels from vehicles passing over different hump and cushion designs (Abbott, Taylor and Layfield, 1997). Body noise levels from vehicles passing over the profiles were generally greater for commercial vehicles with steel leaf suspension than for vehicles with air suspension. Generally, vehicles tended to produce lower levels of body noise when laden.

Simultaneous measurements of ground-borne vibration were also made during this trial to study the variation in vibration levels caused by different vehicle types and profile designs (DOT, 1996b; Watts, Harris and Layfield, 1997). The results showed, as expected, that the vehicles with higher gross vehicle weight (GVW) ratings tended to produce the highest levels of ground-borne vibration. However, the design of the profile, particularly the gradient of the leading ramp, was also found to influence vibration generation. For each profile design the minimum distance which the profile should be positioned from a dwelling to avoid vibration exposure to residents was calculated.

The purpose of these previous test track studies was to provide guidance on the likely levels of noise and vibration generated alongside common profile designs when crossed by a range of vehicle types. These studies showed that the maximum levels of noise and ground-borne vibration alongside traffic calming humps depends on the profile shape as well as the type, load and speed of the vehicle crossing the profile. In the case of ground-borne vibration generation, the local soil type is also critical. It was intended that the results of the research would allow traffic engineers to make more informed selections of traffic calming profile, weighing the required reduction in mean vehicle speeds against local sensitivities regarding noise and vibration. This is of particular importance following recent legislation to deregulate designs of road profile.

The current Highways (Road Humps) Regulations 1999, and the previous Regulations issued in 1996, do not specify an exact hump profile and allow local authorities to install humps on roads with a speed limit of 30 mph or less, without the need for special authorisation, providing the humps are between 25 and 100 mm in height, at least 900 mm long in the direction of travel and with no vertical face greater than 6 mm. The 900 mm length has been found appropriate for profiles known as 'thumps' which should be a maximum of 50 mm high but preferably 40 mm high. Longer lengths are appropriate for speed cushions and 75 mm and 100 mm high humps (DOT, 1996c; Statutory Instrument 1999 No. 1025).

Because of the level of discomfort for bus occupants and delay to emergency vehicles, 100 mm high humps are not usually suitable for bus routes or where the emergency vehicles may be expected to pass over the humps on a regular basis (DOT, 1994). This has led to the widespread use of lower height (75 mm) humps (Webster and Layfield, 1996) and speed cushions (DETR, 1998; Layfield and Parry, 1998) which generally cause less discomfort at a given speed or less delay for the bus operators and emergency services.

Other hump profiles have also been used to reduce passenger discomfort while still controlling vehicle speeds. Humps with a sinusoidal profile have been used in the Netherlands, Denmark and Scotland (Webster and Layfield, 1998). Sinusoidal humps are similar to a round-top hump but have a shallower initial rise (see Figure 1). In the Netherlands, humps with a sinusoidal profile are recommended for use on non-distributor roads subject to speed limits of 20 or 30 kph (CROW, 1998). The literature review by Webster and Layfield indicated that sinusoidal humps are more comfortable for cyclists, and possibly also for car drivers, than round-top or flat-top hump profiles, but found little information as to the degree of difference in discomfort between the hump profiles or on their influence on noise and ground-borne vibration levels.

In order to improve the advice available to local highway authorities, the Charging and Local Transport Division of DETR commissioned TRL to undertake a further comparative evaluation in terms of passenger/rider discomfort, vertical acceleration, vehicle noise generation and ground-borne vibration of a number of humps, all 75mm high, with different profiles. These included sinusoidal humps, round-top humps, flat-top humps with straight ramps and flat-top humps with sinusoidal ramps.

The study trials took place on the central area of TRL's test track facility, in October 1997. Five hump profiles were constructed and vehicles ranging from bicycles to articulated trucks were driven over them at pre-selected speeds. The aim of the trials was to:

i compare the different hump profiles in terms of peak vertical acceleration and the discomfort for passengers, drivers and riders;

ii where possible, to use the above information to estimate the likely crossing speeds of vehicles over the hump profiles if the profiles were to be used on the public roads;

iii assess vehicle noise and ground borne vibration for laden and unladen commercial vehicles;

iv comment on safety and other issues that might show up during the trials.

This report is concerned with the results from the measurements of vehicle noise and ground-borne vibration alongside the hump profiles. The results of the measurements of peak vertical acceleration and passenger/rider discomfort are reported in the 'companion' TRL Report 417 (Sayer *et al*, 1999). The construction of the humps presented an opportunity to supplement the results of the earlier studies comparing noise and vibration generation next to traffic calming profiles. As in the previous vibration study, it was intended to estimate vibration effects for different site conditions by taking into account the generation and propagation of vibration in different soils. With regard to vehicle effects, the study would also allow further investigation of the influence of vehicle type and payload on the generation of noise and ground-borne vibration.

2 Experimental design

2.1 Hump profile selection

Noise and vibration levels were compared alongside five hump profiles during the study. All profiles were 75mm high. As mentioned, the designs were primarily chosen for the study of driver discomfort (Sayer, Nicholls and Layfield, 1999). Part of the purpose of the driver discomfort trial was to assess the traffic calming performance of non-standard designs. The selection included a standard 3.7m long round-top hump, a 3.7m long hump with a sinusoidal profile (non-standard) and a 5m long round-top hump (non-standard). The other two profiles were an 8m long flat-top hump with sinusoidal ramps (non-standard) and an equivalent ramp with standard, straight ramps for direct comparison. The exact dimensions of each profile are given in Table 1. Figures 1 and 2 show cross sections of the hump profiles so that the different profile shapes can be compared. Photographs of the humps are shown in Appendix A.

Table 1 Dimensions of test profiles

Description of profile	*Length[1] (m)*	*Max height (mm)*	*Plateau length (m)*	*Ramp grad-ient*	*Width[2] (m)*	*Taper-ed edge grad-ient*
Sinusoidal, 3.7m long	3.7	75	--	--	3.4	1:4
Round-top, 3.7m long	3.7	75	--	--	3.4	1:4
Round-top, 5.0m long	5.0	75	--	--	3.4	1:4
Flat-top, sinusoidal ramps	8.0	75	6.0	--	3.4	1:4
Flat-top, straight ramps	8.0	75	6.0	1:13	3.4	1:4

[1] In direction of travel
[2] Excluding tapered-edges

A section of the test track located close to the test profiles was also used as a control surface to indicate typical baseline levels of vehicle generated noise and vibration alongside roads without speed control profiles installed. The control surface was a fine textured asphalt material, as was the area of the test track where the humps were constructed. Although not completely level, this surface was expected to produce results typical of many urban roads.

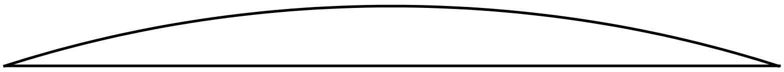
2.2 Vehicle selection

The vehicles selected for the measurements of noise and vibration alongside the profiles were chosen to give potentially 'worst case' levels based on the results from the previous studies. The vehicles were selected from the three

Sinusoidal, 3.7m long (P1)

Round-top, 3.7m long (P2)

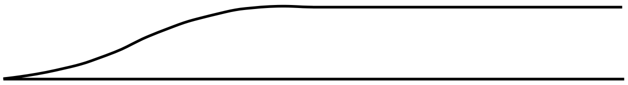
Comparison of sinusoidal and round-top profiles P1 and P2



Round-top, 5m long (P3)

Note: Height dimensions exaggerated to show differences clearly

Figure 1 Cross sections showing profiles of the sinusoidal and round-top humps



Flat-top with sinusoidal ramps, 8m total length (P4)

Flat-top with straight ramps, 8m total length (P5)

Comparison of sinusoidal and straight ramps on profiles P4 and P5

Note: Height dimensions exaggerated to show differences clearly

Figure 2 Cross sections showing profiles of the flat-top humps

categories used previously: light vehicles, buses and commercial vehicles.

The results from the earlier studies indicated that the greatest problems arose from commercial vehicles passing over vertical deflections. The range of results for the commercial vehicles also showed a wide variation because of the diversity of vehicle designs and weights. Three commercial vehicles types were tested. The highest levels of noise measured during the previous studies were generated by a 38t steel suspended articulated tipper vehicle with a maximum permissible gross vehicle weight (GVW) of 38t. It was also known that this type of vehicle was capable of generating high levels of low frequency noise when passing over discontinuities on the road surface due to impacts of the tipper container against the semi-trailer chassis (Harris and Nelson, 1993). However, some of the highest levels of vibration were generated by a 38t GVW air suspended articulated vehicle. To ensure that ’worst case’ vibration levels would be measured during this trial both vehicle types were included. Finally, a 17t GVW dropside truck with steel suspension was selected to represent medium weight commercial vehicles.

One light vehicle and one bus were included in the sample to provide comparative data with that obtained from the heavy vehicles. The vehicle used to represent the light vehicle category was a medium sized car of the same model used in the earlier studies. A double decker bus was used to represent a ‘worst case’ example from this category based on the results from the previous studies. The vehicle chosen was of a typical modern design with air suspension.

Table 2 gives the details of the vehicles used during the study. It should be noted that test vehicle 2 is test vehicle 1 in the unladen condition; likewise, test vehicle 4 is test vehicle 3 in the unladen condition. Vehicle loading considerations are discussed in the next section. Appendix A shows photographs of the test vehicles.

2.3 Vehicle loading

The highest levels of noise and vibration generated by the particular steel and air suspended vehicles tested in the previous trials generally occurred when the vehicles were unladen. It is well established that levels of body noise from a steel suspended commercial vehicle are likely to increase when the vehicle is unladen (Harris and Nelson, 1993). It might be expected that vibration levels would be highest alongside road profiles when crossed by heavily laden vehicles. However, in the case of a vehicle with steel leaf springs the suspension is relatively rigid when the vehicle is unladen. Consequently, little of the vibration energy produced when the vehicle travels over a profile is dissipated by the suspension. The vehicle wheels may even lose contact momentarily with the surface as the wheels run over the top of the profile. The dynamic forces generated on the road may therefore be higher than when the vehicle is unladen, leading to higher vibration levels.

For vehicles fitted with air suspension, the dynamics of the suspension system automatically adjust according to the vehicle load. As well as regulating the ride height and load distribution between the axles, the spring rate is adjusted to provide softer suspension if the vehicle is unladen. Consequently, it might be expected that unladen air suspended vehicles would produce lower levels of ground-borne vibration than equivalent steel suspended vehicles.

To re-examine the influence of vehicle load on noise and vibration generation the two articulated tipper vehicles in the sample were tested in both laden and unladen conditions. The other vehicles, the 17t dropside truck, the bus and the car, were all tested in the unladen condition.

3 Method

3.1 Hump profile construction

The five profiles were positioned in lanes in the centre of a large circular area of the track approximately 270m in diameter (Central Area). The location of the test profiles ensured adequate space for heavy vehicles to reach suitable drive-by speeds and brake safely having passed through the site. Within this area there were no buildings or significant foundation structures that might have affected the transmission or reflection of ground-borne vibration waves. There were also no objects on the track surface that might have caused significant acoustic reflections.

Each profile was approximately half a road width (3.4m) wide. To construct the profiles the perimeters of each hump were marked out on the track and the track surface was cut along the marked lines and the surface removed to a depth of 50 mm. Solid timber side formers, cut to the required profile shapes were then used to line the cut out areas. These were then filled with Portland ready mixed cement, compacted using internal vibrators and tapered into place using a heavy wooden edge. Profiles longer than 4.5m metres were cast in two sections.

3.2 Vehicle drive-by operations

For each test vehicle, drive-by tests were carried out over each of the five hump profiles and the control test surface. Drive-bys were performed at speeds of 15 to 45 km/h at increments of 5 km/h. It was known from previous surveys that this range of speeds would encompass typical crossing speeds recorded on the public highway for the standard profile designs used in this study (Abbott, Phillips and Layfield, 1995). The area of the test track at either end of the site was long enough so that at even the highest speed, with large laden vehicles, it was possible to achieve the constant speed condition well before the profile and sustain it for several vehicle lengths after the rear axle had passed over it. In practice, the higher crossing speeds in the range were considered to be unsafe for certain commercial vehicles either because of the unacceptably high vertical forces experienced by the driver or because of the potential for damaging the vehicle. The driver of the test vehicle was asked to select a gear ratio appropriate to the vehicle speed. Once suitable gear settings had been

Table 2 Details of vehicles used during the study

Veh. No.	*Description*	*Model*	*Suspension type*	*GVW (tonnes)*	*Weight during tests (tonnes)*	*No. of axles*	*Maximum axle weight during tests (tonnes)*	*Indicated distance travelled (approx km)*
1	Tractor & tipper Trailer	DAF95 350	Air	38	36.9	5	9.6	51000
2	Vehicle 1 (unladen)	DAF95 350	Air	38	15.8	5	5.4	51000
3	Tractor & tipper trailer	ERF EC10	Steel	38	38.0	5	11.0	297000
4	Vehicle 3 (unladen)	ERF EC10	Steel	38	16.4	5	5.4	297000
5	Dropside rigid truck	Renault Dodge	Steel	17	7.7	2	4.6	60000
6	Double deck bus	Optare Spectra	Air	17	11.0	2	7.8	233000
7	Passenger car	Ford Sierra 1.8TD	Coil	1.7	1.4	2	0.7	166000

established for a particular vehicle at each test speed, the same ratios were then used throughout the measurement session for all of the profiles. During the drive-bys the test vehicle was driven at a constant speed under a steady throttle setting through the test site. On the approach to each test profile the vehicle was aligned centrally with the hump. An observer was seated in the vehicle with the driver to independently verify that vehicle alignment, gear setting and throttle operation were correct for each test.

3.3 Measurement procedures

The methods of measuring vehicle generated noise and ground-borne vibration was essentially the same as those used during the earlier test track studies carried out in 1995. During the drive-by tests, the vehicle road speed was monitored using a radar speed meter. The remote sensor of this device was set on a tripod and directed towards the approach to the test site to capture road speed as the vehicle passed over the test profile. Actual vehicle speed was recorded for each drive-by along with the gear setting selected for each speed. At least 2 measurements were taken for each drive-by condition. Further tests were performed if the operator judged the results to be significantly different. The exact procedures for the measurement of noise and ground-borne vibration are described below.

3.3.1 Noise measurements

During each drive-by the maximum sound pressure level was recorded. The noise measuring instrument was set-up to capture the maximum A-weighted and C-weighted levels during each measurement period[2]. It was intended that the C-weighted noise results would more clearly indicate any large increases in low frequency noise as might occur as the result of body noise generation (e.g. movement of tipper bodies) (Harris and Nelson, 1993). The time weighting was set to 1/4 second exponential averaging which is equivalent to the standard 'fast' response setting used on sound level meters. The calibration of the noise measurement system was checked before and after each measurement session using a 1kHz calibration tone generator fitted over the microphone.

Figure 3 shows the layout of the test site and measurement equipment. Figure 4 shows photographs of the test site taken during drive-by tests. The microphone was placed alongside the profile being tested at the standard vehicle noise measurement position described in the EC vehicle noise type approval testing procedure (European Communities, 1992). This requires that the microphone be orientated with the microphone diaphragm vertical, facing towards the centre of the test site at a distance of 7.5m from the centre-line of the vehicle path. The standard microphone height for this procedure is 1.2m above the test track surface. The microphone was located midway along the length of the test profile.

3.3.2 Ground-borne vibration measurements

Figure 3 shows the configuration of the ground-borne vibration measuring equipment. An array of 3 geophones

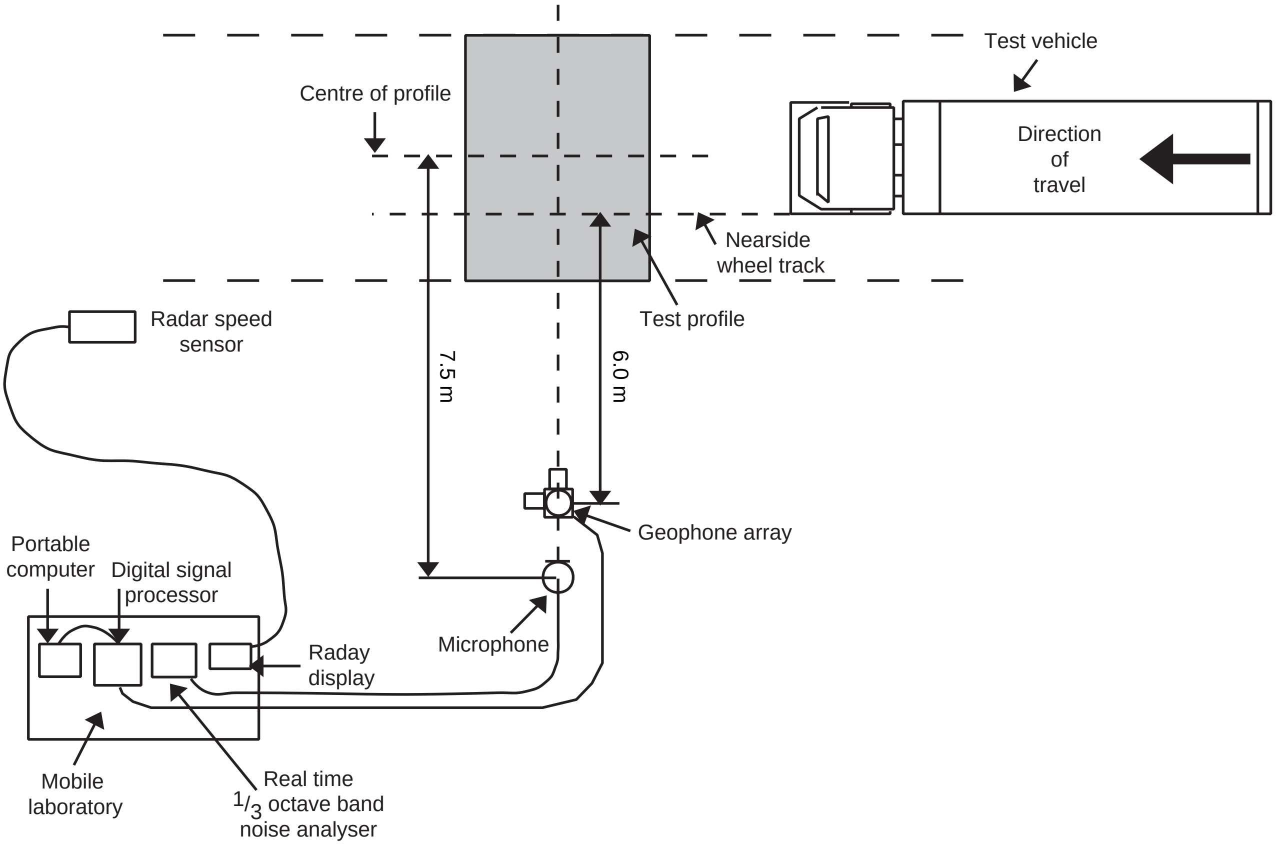


Figure 3 Layout of test site and measurement equipment

(Test vehicle 6)

(Test vehicle 2)

Figure 4 Vehicle drive-by showing geophone and microphone locations was mounted firmly on the surface of the test track alongside the profile under test to detect vibrations along 3 orthogonal axes (vertical, radial and transverse). The geophones were attached to the track surface with a bolt which screwed tightly into threaded inserts set into the surface at the appropriate location. The mounting position alongside each test profile was established in line with the centre of the profile at a distance of 6m from the nearside wheel track. This distance was established as a standard reference distance for measurement of vehicle generated ground-borne vibration during earlier studies (Watts, 1989). For certain tests, such as those alongside the control surface, a threaded insert had not been set into the track at a suitable distance from the nearside wheel track. In these cases the geophones were mounted onto the track surface at the correct location using plaster of Paris.

The geophones were connected to a multi-channel signal processor which amplified and then digitised the input signals at a sampling rate of 1 kHz. This device was connected via a data bus to a portable computer which scaled and recorded the digitised particle velocity signal using specially developed software. The calibration of the measurement system was checked by connecting a known signal level from a calibrated precision voltage source to each of the inputs of the signal processor. The signal level displayed on the computer was then noted to ensure the scaling was correct on each channel for a typical signal strength. To configure the system for the measurements, the particular sensitivity value of each geophone was entered into the program to ensure that the signal from each device was scaled accurately. This procedure was carried out before and after any measurements were taken, as well as periodically during the measurement sessions. The absolute sensitivity of each geophone had been checked and noted by the manufacturer before the study to confirm that transducers were functioning within their specified accuracy tolerances.

The system was configured to capture a 10 second time record of particle velocity. The sampling period was commenced on the operation of a manual trigger switch which was activated as the vehicle approached the test profile. Following each drive-by, the peak particle velocity (PPV) value in each axis was recorded. Prior to any vehicle measurements, levels of background vibration were recorded to determine the lowest possible levels of vehicle generated vibration that would be discernible during any given measurement session. This procedure also served to highlight any faults with the measurement system.

3.4 Analysis procedures

3.4.1 Noise measurement data

The maximum recorded levels of A and C-weighted noise were entered into a computer data record. For each drive-by condition two measurement results were entered and the mean of the two values calculated. If there were any significant inconsistency in the results a third test was carried out, the two most consistent results were entered into the data record. Generally, the drive-by tests were found to be repeatable and the measurement results of successive tests were very similar. Only occasionally was it judged necessary to carry out more than two tests for any drive-by condition.

3.4.2 Ground-borne vibration data

As with the noise data, the levels of peak vibration were entered into a computer record. Again, two measurement results were entered for each drive-by condition and the mean of the two values calculated.

4 Results

4.1 Results obtained at different vehicle speeds

4.1.1 Noise levels and vehicle speed

Figures 5 to 7 show drive-by noise and speed relations for the three vehicle categories. For each profile, the averaged measurement results are shown at each drive-by speed. Background noise levels were at least 10 dB(A) below the measured noise levels during the tests.

i Light vehicle

The vehicle speed and maximum noise (L_{Amax}) relations for the light vehicle are shown in Figure 5. It can be seen that, generally, noise level increased as the drive-by speed increased. Between the speeds of 15 - 20 km/h, and 35 - 40 km/h the figure shows that drive-by noise reduced. This corresponded with changes in gear ratio causing reductions in engine speed, and hence lower noise levels. The variation in noise level alongside the different profiles was within 2.5 dB(A) at any given speed across the range. Some of the highest noise levels were measured alongside the control surface. This would indicate that the texture of this surface gave rise to slightly higher levels of tyre/road noise than the lightly brushed concrete texture of the test profiles. This result highlights the fact that the surface type of the profile can cause a change in drive-by noise levels of vehicles passing over it. Clearly, for this vehicle, the profiles did not generally cause drive-by noise to increase.

ii Bus

The relation between maximum noise level and speed for the double decker bus (Figure 6) also shows a general increase in noise level with increasing speed. The results obtained during drive-bys at 15 km/h show a wide variation in noise level. This was because the vehicle was fitted with an automatic gearbox which changed from first to second gear at a speed of approximately 15 km/h. Although every effort was made to ensure the same gear was selected at this speed, it was not always possible to be certain of this. Consequently, some of the variation in noise level obtained for the various profiles at this speed was almost certainly due to the effect of different gear settings.

For this vehicle the noise levels generated alongside the hump profiles were generally greater than the noise measured next to the control surface. The increases were typically within the range 0 - 4 dB(A) at speeds greater than 15 km/h. The flat-top profile with the straight ramp caused some of the highest noise levels over the speed range examined.

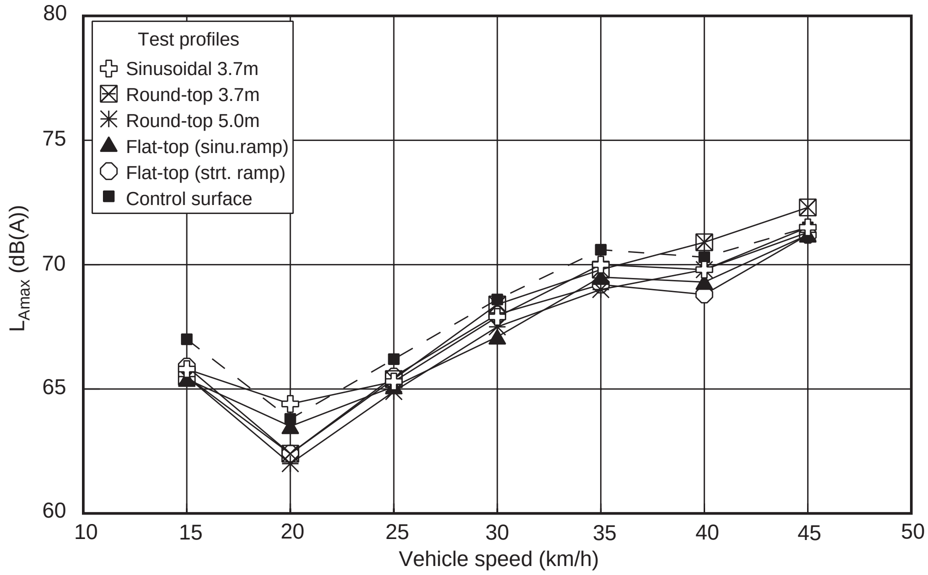


Figure 5 Relation between noise level and vehicle speed — light vehicle (vehicle 7: passenger car, coil suspension)

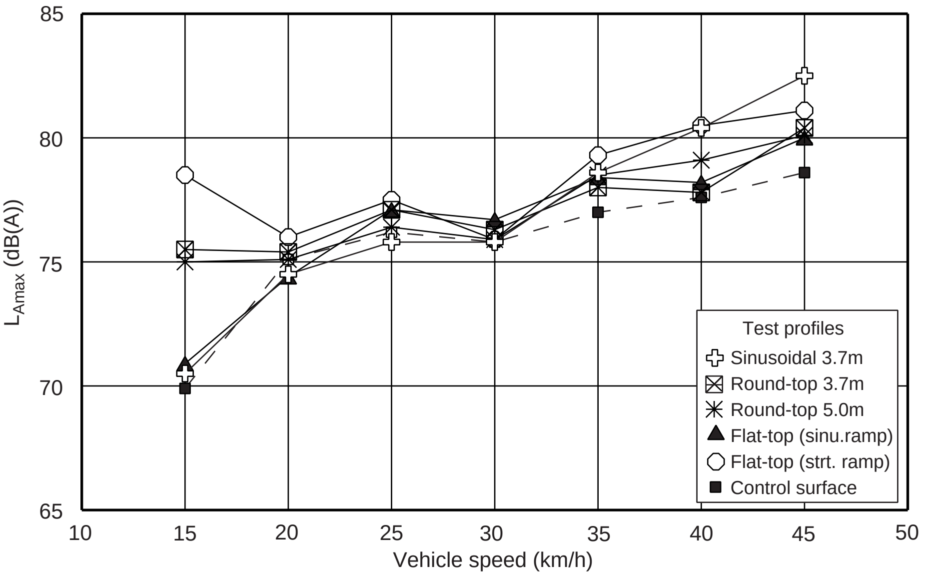
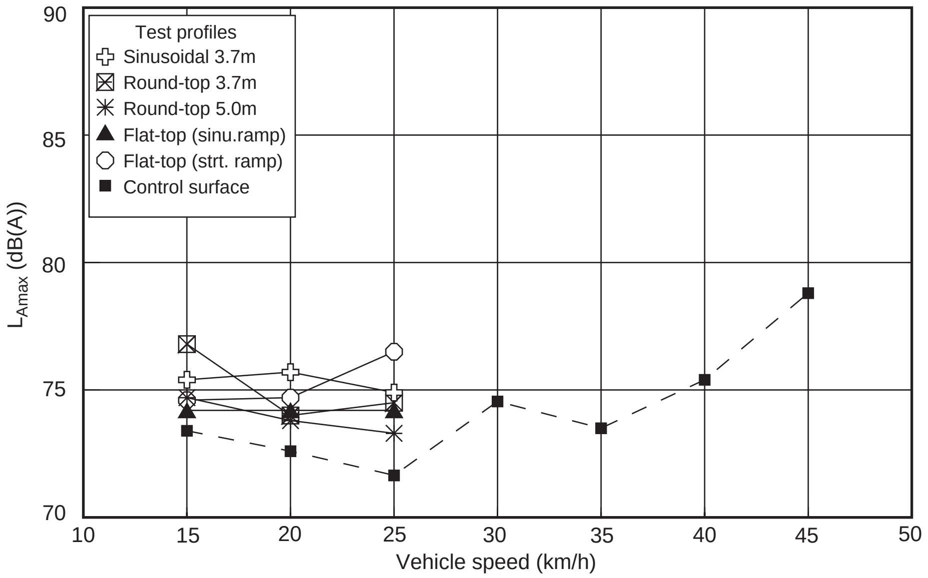
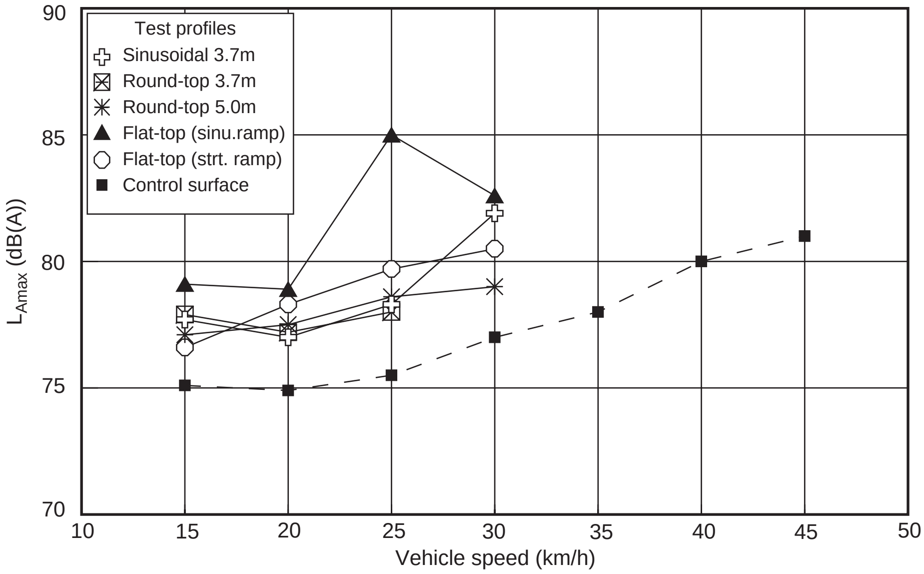


Figure 6 Relation between noise level and vehicle speed — bus (vehicle 6: double deck bus, air suspension)

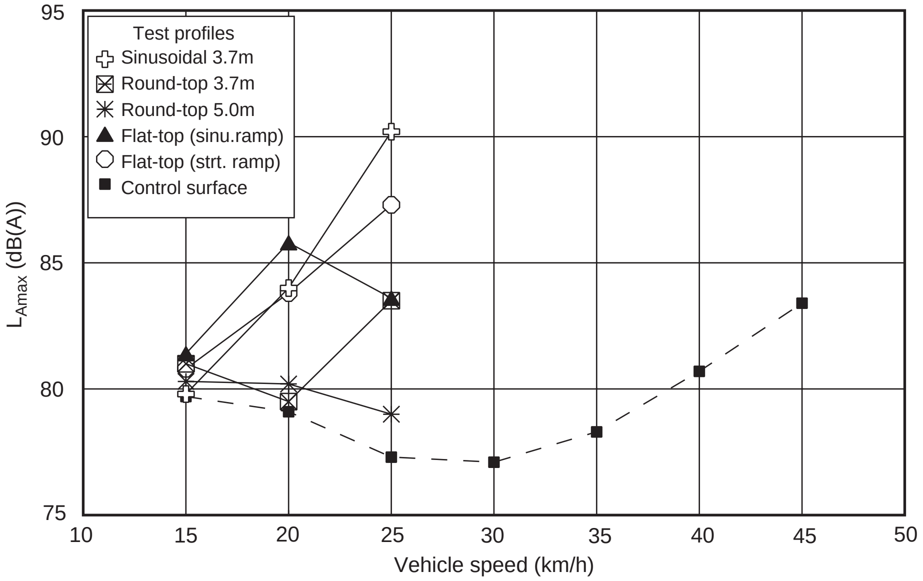


(a) Vehicle 1: tractor and tipper trailer, air suspension — laden

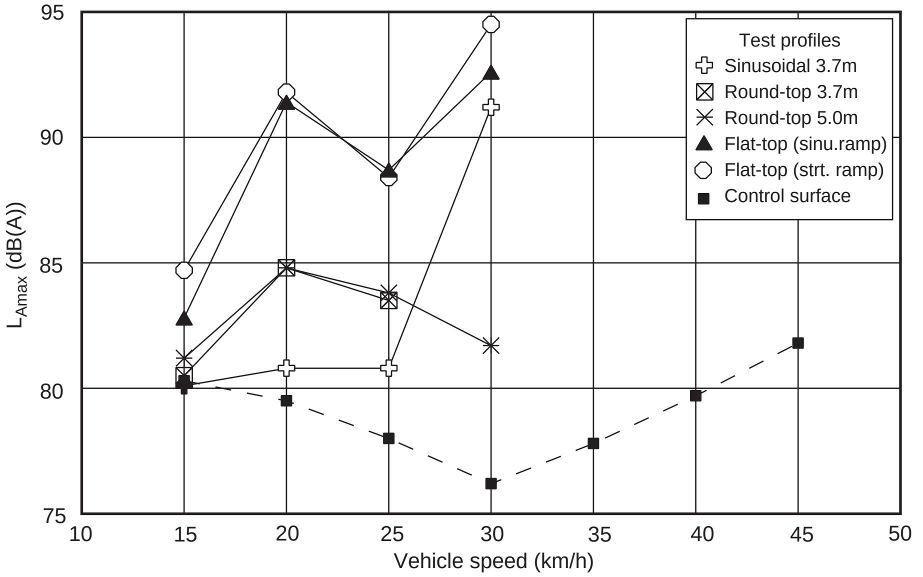


(b) Vehicle 2: tractor and tipper trailer, air suspension — unladen

Figure 7 Relation between noise level and vehicle speed — commercial vehicles

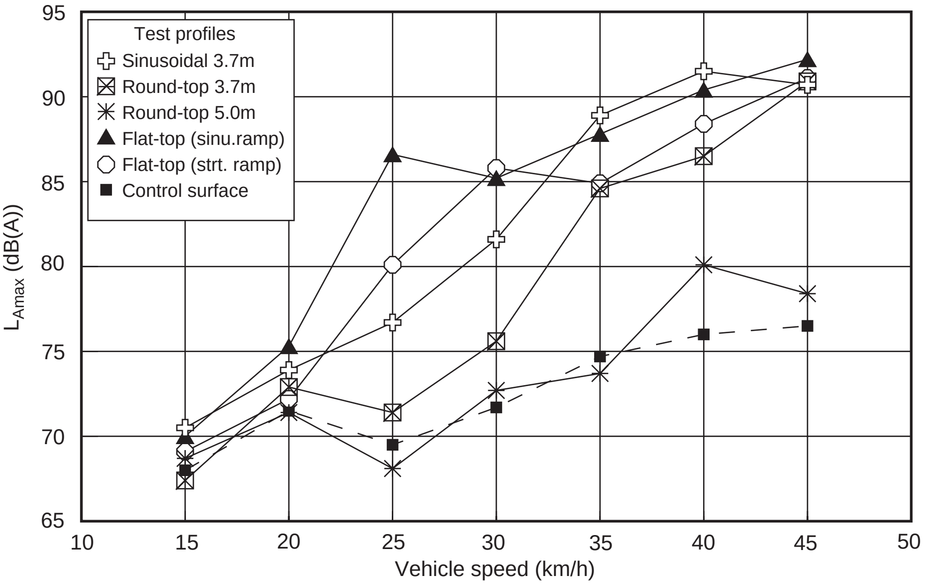


(c) Vehicle 3: tractor and tipper trailer, steel suspension — laden



(d) Vehicle 4: tractor and tipper trailer, steel suspension — unladen

Figure 7 (continued) Relation between noise level and vehicle speed — commercial vehicles



(e) Vehicle 5: dropside truck, steel suspension — unladen

Figure 7 (continued) Relation between noise level and vehicle speed — commercial vehicles

iii Commercial vehicles

Figures 7(a-e) show the relation between maximum noise level and speed for the commercial vehicles. The effect of vehicle load on noise generation for both air and steel suspension designs will be examined in detail in Section 4.2.1.

Figures 7(a) and 7(b), compare the results obtained for the 5-axle articulated tipper truck with air suspension in its laden and unladen state. These are described as test vehicles 1 and 2 respectively. The maximum crossing speed was restricted to below 45 km/h in this case as the driver considered that the higher test speeds were unrepresentative for this type of vehicle and might have caused damage to the vehicle.

In the laden state (Figure 7(a)) the noise levels measured alongside the hump profiles showed a relatively small variation (within approximately 3 dB(A)) at each speed across the range 15 - 25 km/h. Over this small speed range there was no apparent relation with speed, even for the control surface. However, the gear setting was increased at each speed increment, as judged appropriate by the driver, causing engine speed to reduce over the speed range. It is expected, therefore, that power train noise would have reduced slightly over this range of low speeds. This factor, combined with the slight increase in tyre noise expected with increasing speed, produced the overall absence of any functional relationship with speed. Noise levels alongside the hump profiles were typically at least 1 dB(A) greater than the noise next to the control surface. In the unladen state (Figure 7(b)) the flat-top (sinusoidal ramp) profile caused a pronounced peak in noise level at a crossing speed of 25 km/h, which was 5 dB(A) greater than any other profile. The two round-top profiles generally caused lower noise levels to be generated across the speed range relative to the other test profiles. However, the results from these profiles were still at least 1-2 dB(A) greater than the results obtained for the control surface. Noise levels were distinctly higher when this vehicle was unladen.

It might be expected that the results obtained for the unladen vehicle travelling on the control surface would be the same as those obtained for the laden vehicle. This is because, although there would be a greater potential for body noise generation from an unladen vehicle, the sources would be much less likely to be excited when travelling over the relatively smooth control surface. In this case however, it can be seen that the noise levels obtained alongside the control surface were greater when the vehicle was unladen by about 2–5 dB(A) over the speed range. The main reason for this was that this particular tipper semi-trailer, when unladen, was prone to generate low levels of body noise even when travelling on the relatively smooth control surface. The small undulations present on the track surface caused small movements of the tipper body and doors leading to some noise generation in addition to the power train and tyre/road noise. However, the results give the comparative difference between noise levels taken alongside the profiles and the control surface. The results show that drive-by noise measured alongside the hump profiles was dominated by body noise generation.

Figures 7(c) and 7(d), compare the results obtained for the 5-axle articulated tipper truck with steel suspension in its laden and unladen state. These are described as test vehicles 3 and 4 respectively. Again, the maximum crossing speed was restricted to below 45 km/h as higher crossing speeds were considered by the driver to be unrepresentative for this type of vehicle and because of concerns about damage to the vehicle.

In the laden state (Figure 7(c)) the noise levels measured alongside the individual hump profiles showed a much larger variation across the speed range (up to 10 dB(A)) compared with the laden vehicle with air suspension (up to 3 dB(A)). Noise levels alongside the hump profiles generally increased across this small speed range. The noise level alongside the control surface reduced with vehicle speed which can, again, be attributed to reductions in engine speed as progressively higher gear ratios were selected at each speed. At 25 km/h the noise levels recorded alongside the hump profiles were up to 12.5 dB(A) greater than the equivalent level recorded next to the control surface. The two round-top profiles generally caused lower noise levels to be generated over the speed range relative to the other test profiles. The results from these quietest hump profiles were 0 - 2 dB(A) greater than the results obtained for the control surface. In the unladen state (Figure 7(d)) there was a much greater variation in noise levels caused by different profile designs and the noise levels were generally considerably higher across the speed range. The exception to this was the 3.7m sinusoidal profile design which gave levels that were much less than those obtained with the laden vehicle at 20 and 25 km/h. For the unladen vehicle the two flat-top designs caused noise levels that were typically considerably greater than the levels measured alongside the other hump types.

Figure 7(e) shows the relationship between drive-by noise level and vehicle speed for vehicle 5, the unladen 2-axle 17t rigid truck. For this vehicle, tests were carried out up to the maximum test speed of 45 km/h. The fiigure shows that noise levels generally increased with increasing speed. The profiles causing least noise were the round-top designs, notably the 5m round-top profile results were similar to those obtained alongside the control surface.

4.1.2 Ground-borne vibration levels and vehicle speed

Figures 8 to 10 show vehicle generated ground-borne vibration and speed relations for the three vehicle categories. As expected, the dominant axis of vibration was in the vertical direction for all combinations of profile and vehicle type. Typically, peak vibration levels in the radial and transverse direction were not significant when compared with the vertical levels recorded under similar conditions. Consequently, the results reported here are concerned only with quantifying the peak vibration amplitudes in the vertical direction. Like the noise data, the two measurement readings at each drive-by speed were averaged and the resulting value is plotted at each vehicle speed increment.

Background vibration in the vertical plane was recorded at levels varying between 0.03 - 0.08 mm/s peak particle velocity (PPV) on different days throughout the period of the trials.

i Light vehicle

The vehicle speed and vertical PPV relations for the light vehicle are shown in Figure 8. At the time that these measurements were made the levels of background vibration were measured between 0.04 - 0.06 mm/s PPV. It can be seen therefore that the vehicle generated vibration alongside the profiles was possibly masked at the lower drive-by speeds by background levels of vibration. The results recorded alongside the control surface were certainly not discernible above background levels. Some of the highest levels were caused by the round-top profiles across the speed range. It should be noted though, that relative to the vibration levels recorded alongside the profiles during drive-bys with the larger vehicles, the levels obtained with the light vehicle were very low.

ii Bus

Figure 9 shows the equivalent results for the bus. In this case there is a general increase in vibration level as vehicle speed increases. As would be expected, the control surface gave the lowest levels of vibration. The flat-top (straight ramp) hump and the round-top 3.7m hump consistently gave some of the highest levels across the speed range.

iii Commercial vehicles

Figures 10(a) to (e) show the relation between ground-borne vibration and speed for the commercial vehicles. The effect of vehicle load on vibration generation for both air and steel suspension designs will be examined further in Section 4.2.2.

Figures 10(a) and 10(b) compare the results obtained for the 5-axle articulated tipper truck with air suspension in its laden and unladen state. As discussed, the maximum crossing speed was restricted below 45 km/h. In the laden state (Figure 10(a)) the vibration levels measured alongside the hump profiles showed a relatively small variation (within approximately 0.12 mm/s PPV) at each speed across the range 15 - 25 km/h. Over this limited speed range, vibration level increased with increasing vehicle speed for each of the profiles and the control surface. Vibration levels measured alongside the hump profiles were consistently greater than those recorded next to the control surface. The flat-top (straight ramp) hump caused relatively high levels of vibration at 20 and 25 km/h compared to the other results obtained for this vehicle. In the unladen state (Figure 10(b)) vibration level also increased with increasing speed for all of the hump profiles. For this vehicle the highest levels of vibration were caused by the flat-top (straight ramp) hump.

Figures 10(c) and 10(d) compare the results obtained for the 5-axle articulated tipper truck with steel suspension in its laden and unladen state (vehicles 3 and 4 respectively). In the laden state (Figure 10(c)) vibration levels alongside the hump profiles generally increased across this small speed range. The flat-top (straight ramp) and 3.7m round-top hump profiles caused the highest levels of vibration for this vehicle. In the unladen state (Figure 10(d)) vibration levels again increased with speed. In this case there was a much greater variation in vibration levels caused by different profile designs and the vibration levels were generally

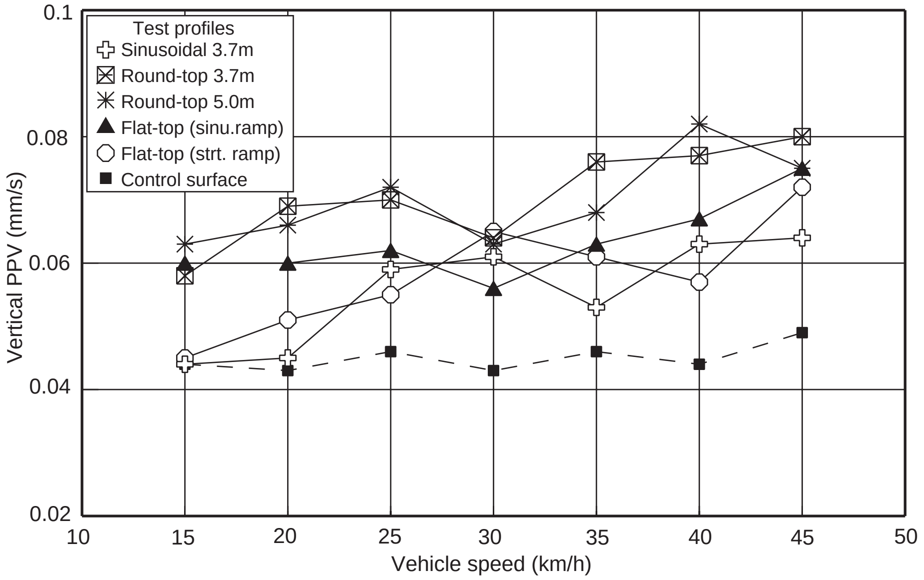


Figure 8 Relation betweeen vertical PPV and vehicle speed — light vehicle (vehicle 7: passenger car, coil suspension)

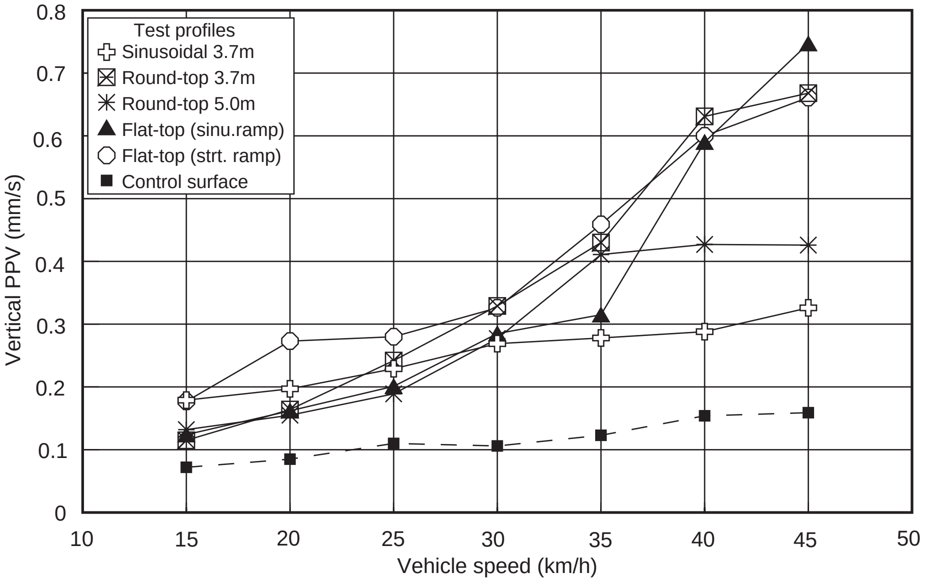
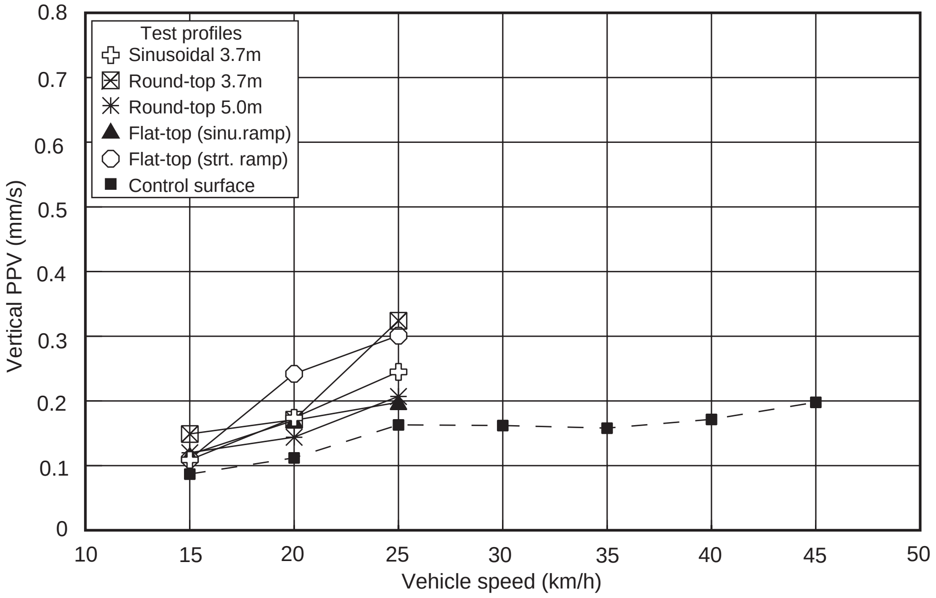
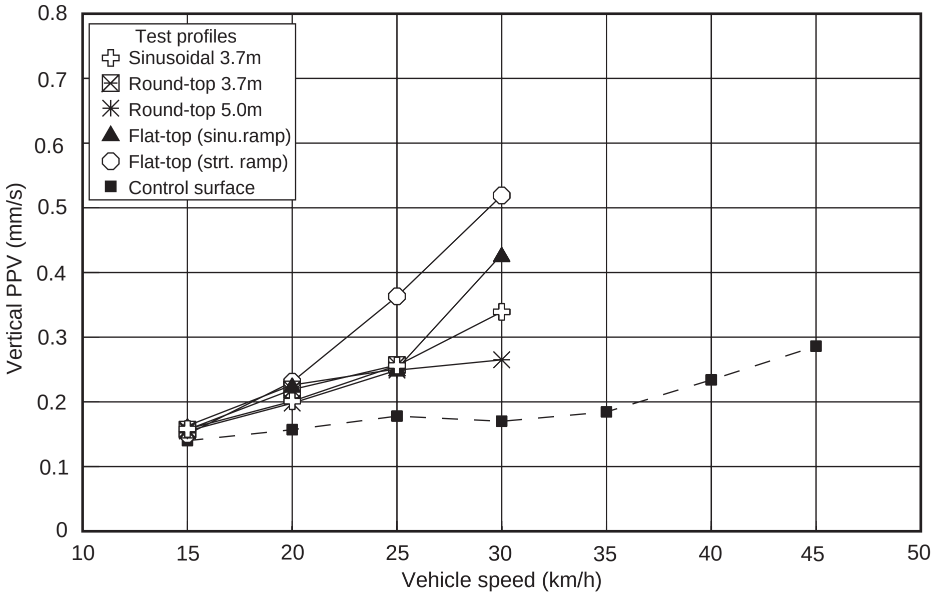


Figure 9 Relation between vertical PPV and vehicle speed — bus (vehicle 6: double deck bus, air suspension)

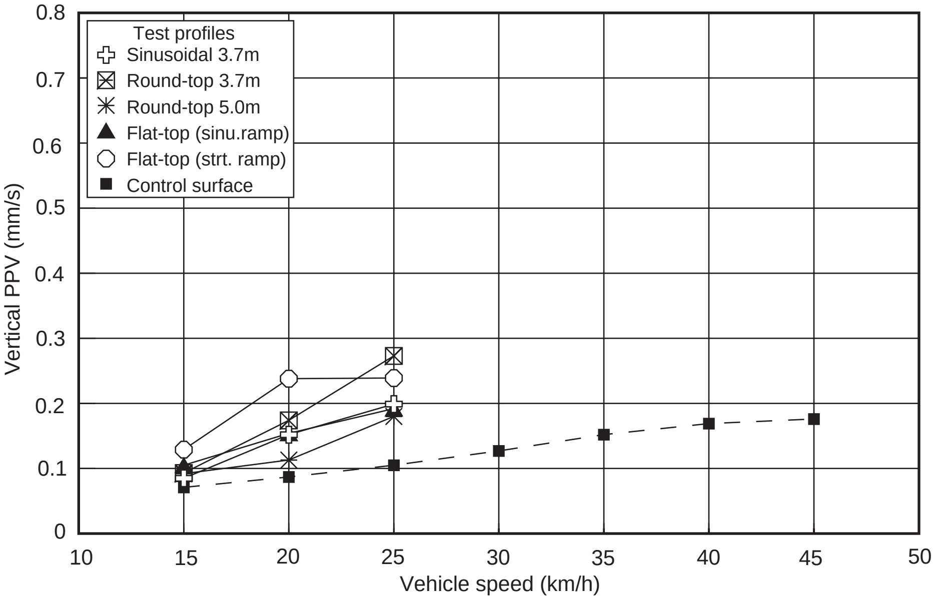


(a) Vehicle 1: tractor and tipper trailer, air suspension — laden

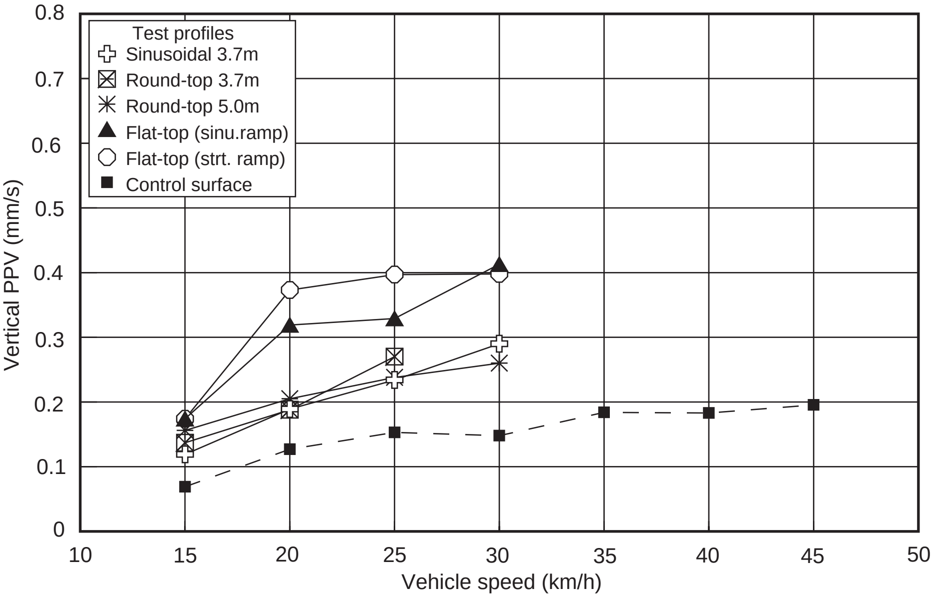


(b) Vehicle 2: tractor and tipper trailer, air suspension — unladen

Figure 10 Relation between vertical PPV and vehicle speed — commercial vehicles

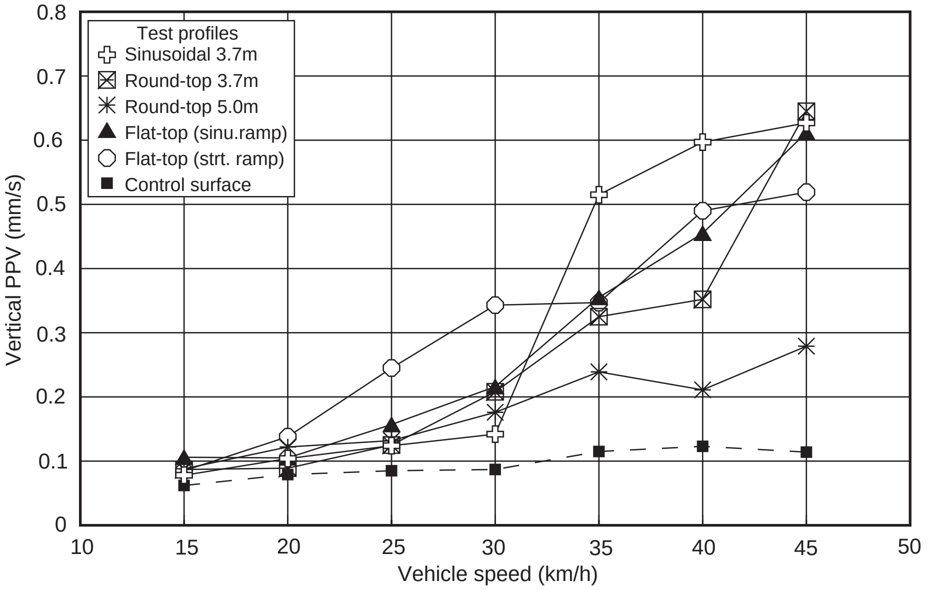


(c) Vehicle 3: tractor and tipper trailer, steel suspension — laden



(d) Vehicle 4: tractor and tipper trailer, steel suspension — unladen

Figure 10 (continued) Relation between vertical PPV and vehicle speed — commercial vehicles



(e) Vehicle 5: dropside truck, steel suspension — unladen

Figure 10 (continued) Relation between vertical PPV and vehicle speed — commercial vehicles

considerably higher across the speed range. For the unladen vehicle the two flat-top designs caused vibration levels that were typically, considerably greater than the level measured alongside other hump types.

Figure 10(e) shows the relationship between vibration level and vehicle speed for vehicle 5, the unladen 2-axle 17t rigid truck. The fiigure shows that noise level generally increased with increasing speed. The profiles causing the highest levels of vibration were the flat-top (straight ramp) hump over the lower speed range, and the sinusoidal 3.7m hump at the higher speeds.

For the sample of commercial vehicles tested, the 5m round-top hump generally gave vibration levels that were amongst the lowest measured relative to the other profiles.

4.2 Results obtained with different vehicle loads

4.2.1 Noise levels and vehicle load

Figure 11(a) compares the noise levels measured for the 5-axle tipper truck with air suspension in the laden and unladen state. The results are those obtained during drive-bys at a single reference speed of 25 km/h. Clearly the noise levels were greater when the vehicle was unladen, the increases ranging from 3 - 10 dB(A) across the different profiles. The greatest increase occurred alongside the flat-top (sinusoidal ramp) hump.

As noted in Section 4.1.1, the noise level measured next to the control surface was approximately 3 dB(A) greater when the vehicle was unladen. This was partly attributed to the wet conditions increasing levels of tyre/road noise when the vehicle was tested in the unladen state. However, body noise was the dominant noise source during the drive-bys over the hump profiles, therefore, significant noise increases would still have occurred with the unladen vehicle had the conditions been dry during the tests.

Figure 11(b) shows the equivalent comparison between the results obtained for the articulated tipper truck with steel suspension in the laden and unladen condition during drive-bys at 25 km/h. In this case the effect of vehicle load is less distinct. For the two flat-top humps and the 5m round-top the results obtained in the unladen state were greater by between 1 - 5 dB(A). The opposite effect occurred at the 3.7m sinusoidal hump. In this case the drive-by noise level was significantly greater when the vehicle was laden. It was noted during the tests that significant body noise was generated when the laden vehicle passed over this profile.

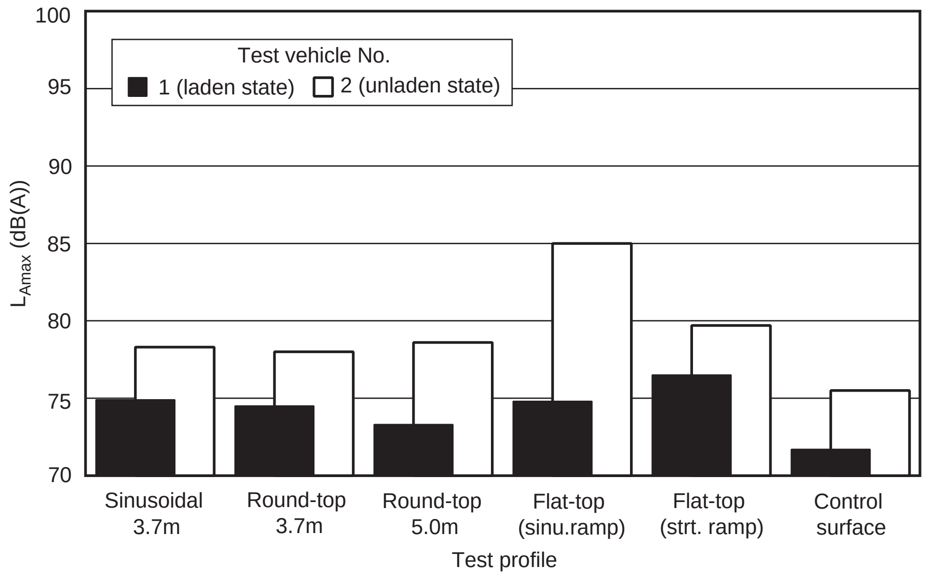
4.2.2 Ground-borne vibration and vehicle load

Figure 12(a) compares the vibration levels measured for the 5-axle tipper truck with air suspension in the laden and unladen state. The results are those obtained during drive-bys at a single reference speed of 25 km/h. The vibration levels were greater when the vehicle was unladen with the exception of the result for the 3.7m round-top hump. The increases in vibration level were less than 0.1 mm/s PPV.

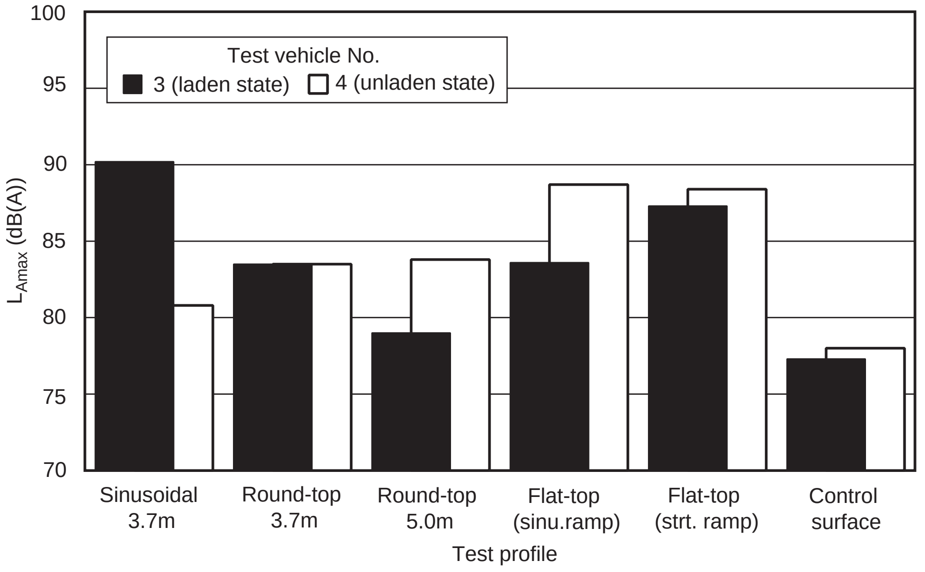
Figure 12(b) shows the equivalent comparison between the results obtained for the articulated tipper truck with steel suspension in the laden and unladen condition during drive-bys at 25 km/h. In this case the increases in vibration level were more pronounced when the vehicle was unladen. Again, the only profile where no increase was measured was the 3.7m round-top hump. Increases ranged between 0.03 - 0.15 mm/s PPV. The greatest differences were observed for the two flat-top humps.

4.3 Comparison of results obtained alongside the different hump profiles

Figure 13 compares the highest noise and vibration levels measured alongside each profile during drive-bys at a common reference speed of 25 km/h. The figure shows the

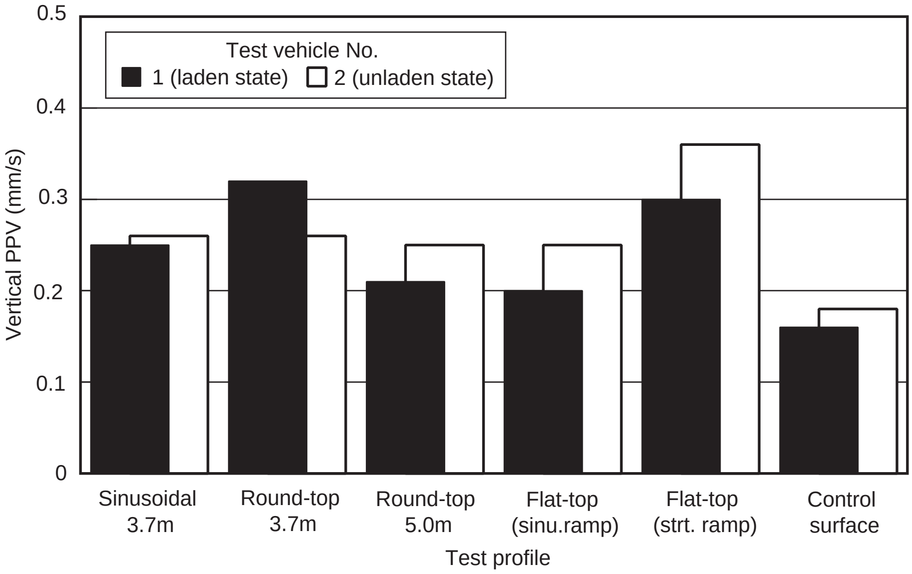


(a) Test vehicles 1 and 2 (tractor and tipper trailer — air suspension)

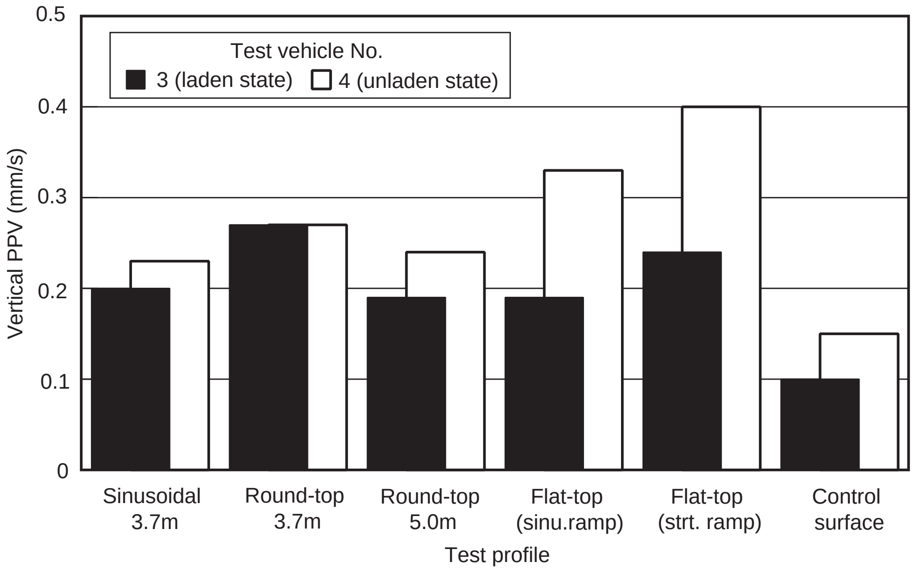


(b) Test vehicles 3 and 4 (tractor and tipper trailer — steel suspension)

Figure 11 Comparison of maximum noise level generated by laden and unladen vehicles (all drive-bys at 25 km/h)

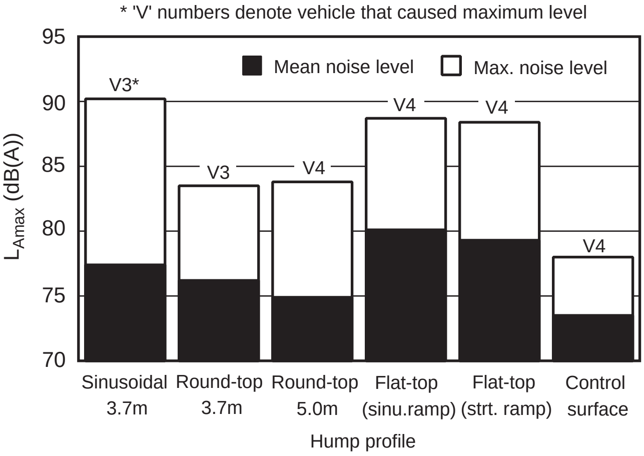


(a) Test vehicles 1 and 2 (tractor and tipper trailer — air suspension)

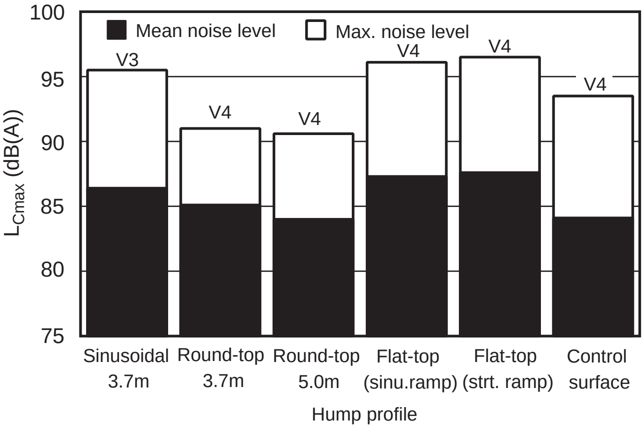


(b) Test vehicles 3 and 4 (tractor and tipper trailer — steel suspension)

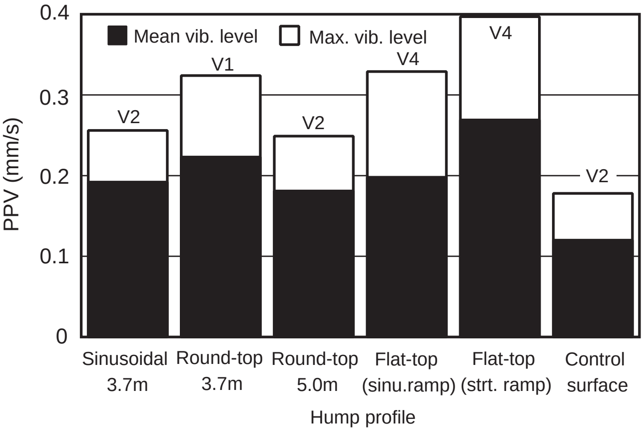
Figure 12 Comparison of ground-borne vibration generated by laden and unladen vehicles (all drive-bys at 25 km/h)



(a) Maximum and mean L_{Amax} noise levels



(b) Maximum and mean L_{Cmax} noise levels



(c) Maximum and mean ground-borne vibration levels

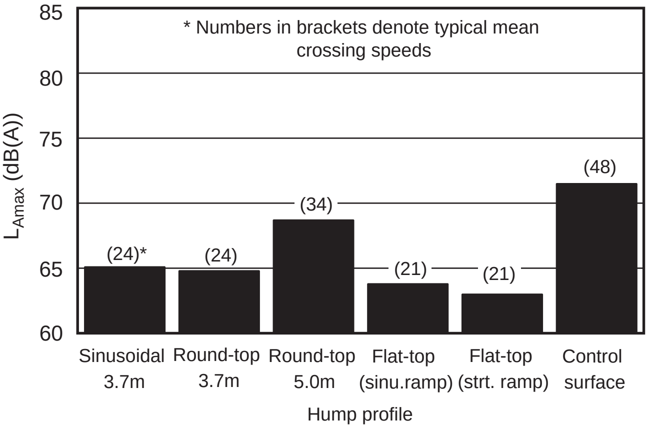
Figure 13 Maximum and mean noise and ground-borne vibration levels for each hump profile (all test vehicles at 25 km/h)

highest of all the individual results obtained across the whole vehicle sample as well as the mean average of the results across the vehicle sample. The maximum result gives some comparison of the likely worst-case levels generated alongside each profile design at a common reference speed. The mean of the noise and vibration results is intended to give an indication of the relative, overall levels of noise and vibration exposure caused by the different profile designs assuming a mixed flow of vehicle types.

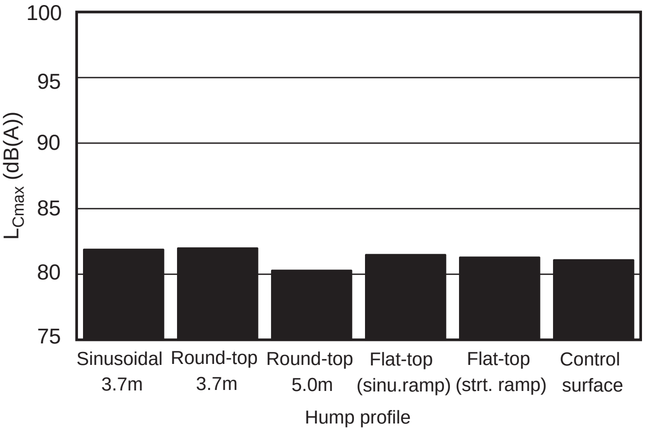
Although this gives a useful comparison of the levels caused by the different profile shapes at a given speed, the comparison is not representative of the relative levels that would be generated in practice. This is because the typical crossing speeds would differ for the various hump profiles depending on the degree of discomfort perceived by the driver when passing over each design. The comparison of maximum noise and vibration levels at typical crossing speeds for each individual profile is made in Figure 14 to 16. These results give a more meaningful comparison of noise and vibration levels likely to be caused if the different profiles were installed on the public highway. Figure 14 and Figure 15 show these results for the light vehicle and for the bus respectively. Figure 16 shows the results obtained for the commercial vehicles group. As the commercial vehicle category comprised a range of vehicle types, the figure shows the maximum and mean values for the vehicle group. Most of the typical crossing speeds do not coincide with the actual crossing speeds used during the study. Where necessary, the values shown in the figures have been calculated by interpolating between the results obtained at test speeds above and below the typical crossing speed. Table 3 gives the typical crossing speeds for each vehicle category passing over each profile design used in the study. The typical mean speeds for light and heavy vehicles passing over the standard hump designs were determined from survey data recorded at road sites where the various profile designs had been installed (Abbott, Phillips and Layfield, 1995). Typical crossing speeds for the non-standard hump designs were based on

Table 3 **Estimated typical speeds for vehicles crossing hump profiles on public roads**

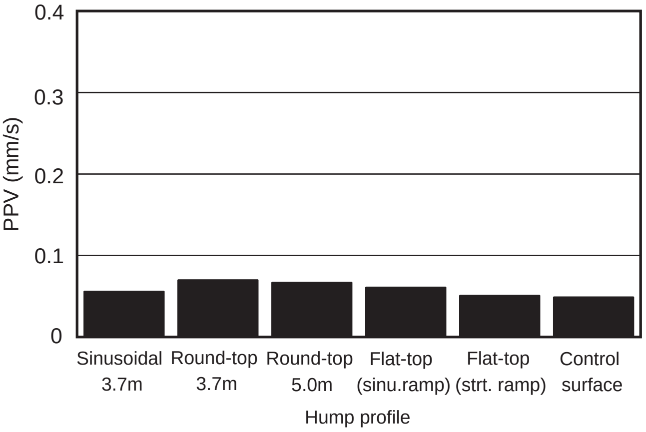
	Vehicle category		
Test profile	*Light*	*Buses*	*Commercial*
Sinusoidal (3.7m long)	24 km/h (15 mph)	18 km/h (11 mph)	18 km/h (11 mph)
Round-top (3.7m long)	24 km/h (15 mph)	18 km/h (11 mph)	18 km/h (11 mph)
Round-top (5.0m long)	34 km/h (21 mph)	20 km/h (12 mph)	20 km/h (12 mph)
Flat-top (sinusoidal ramp)	21 km/h (13 mph)	18 km/h (11 mph)	18 km/h (11 mph)
Flat-top (straight ramp)	21 km/h (13 mph)	18 km/h (11 mph)	18 km/h (11 mph)
Control surface	48 km/h (30 mph)	43 km/h (27 mph)	43 km/h (27 mph)



(a) L_{Amax} noise levels

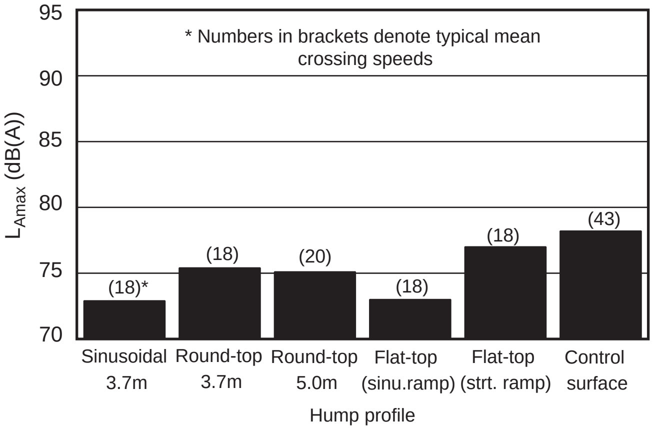


(b) L_{Cmax} noise levels

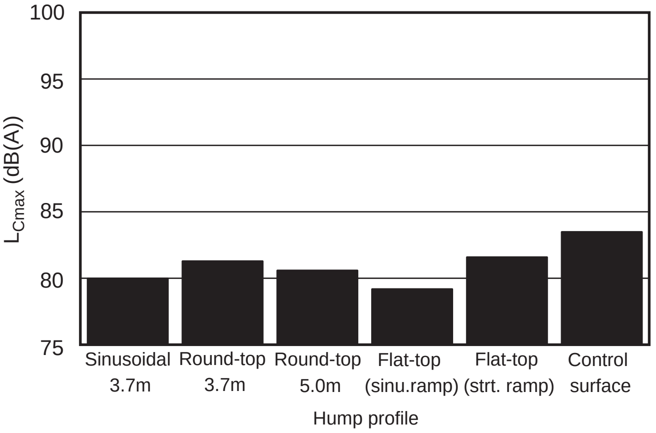


(c) Ground-borne vibration levels

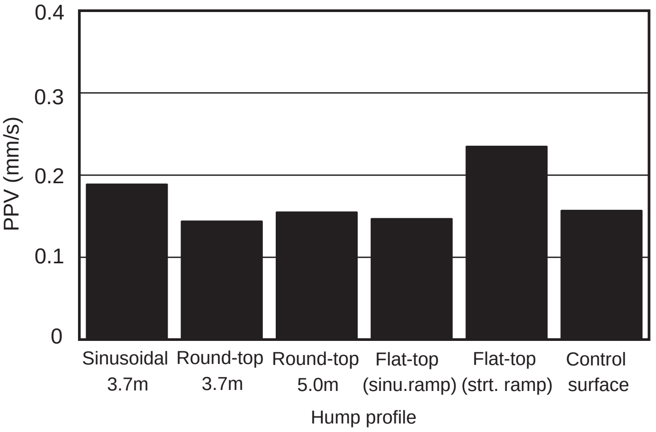
Figure 14 Noise and ground-borne vibration levels for each hump profile (light vehicle only — typical mean crossing speed)



(a) L_{Amax} noise levels

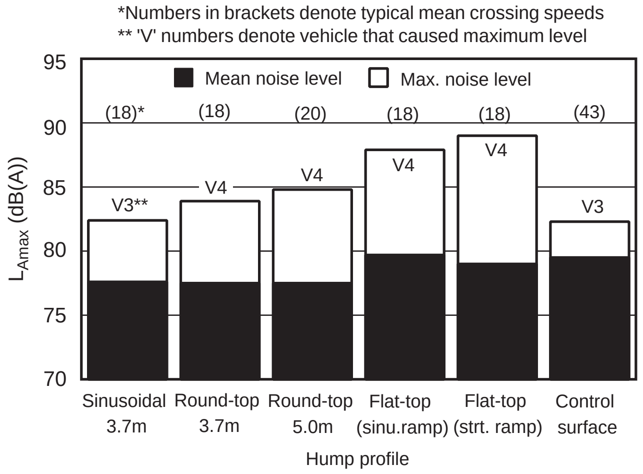


(b) L_{Cmax} noise levels

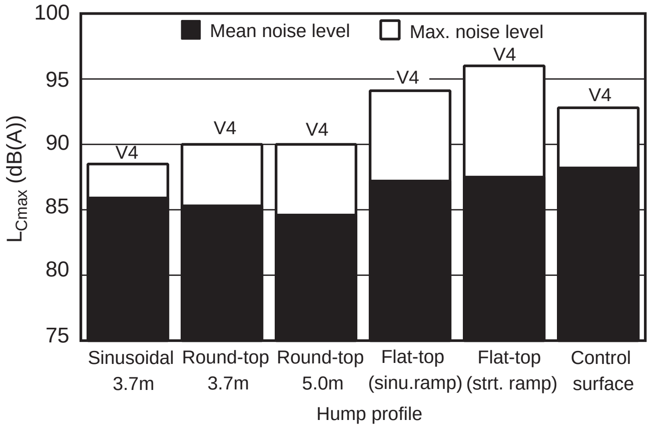


(c) Ground-borne vibration levels

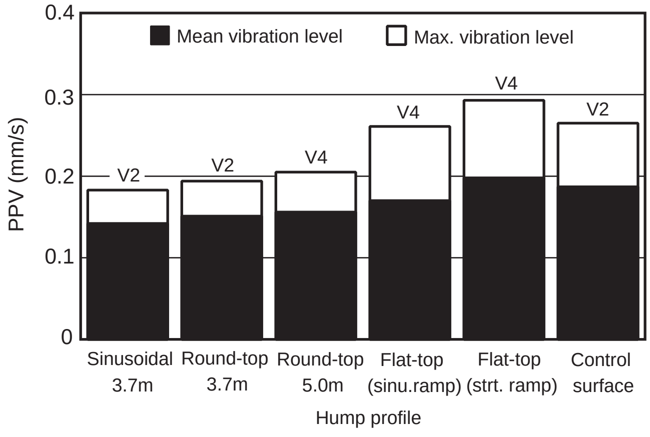
Figure 15 Noise and ground-borne vibration levels for each hump profile (bus only — typical mean crossing speed)



(a) Maximum and mean L_{Amax} noise levels



(b) Maximum and mean L_{Cmax} noise levels



(c) Maximum and mean ground-borne vibration levels

Figure 16 Noise and ground-borne vibration levels for each hump profile (commercial vehicles — typical mean crossing speed)

the preferred crossing speeds adopted at the limited number of road sites where these experimental profiles had been installed. Tables B1 - B4 in Appendix B give the actual numerical values of the results shown graphically in the figures. The numbers shown in brackets next to the results in the tables denote the rank order of each result relative to the highest level. Typical speeds on a road without humps will depend on a range of factors including speed limit, width of road, gradient and presence of parked vehicles. For this study a speed of 43 km/h was used to provide a basis for comparison.

Noise level is given in terms of A and C-weighted noise.

4.3.1 Noise levels alongside different hump profiles

i At a reference speed of 25 km/h

The maximum A-weighted noise level results obtained across the vehicle sample (Figure 13(a)) show that the single highest level was recorded alongside the 3.7m sinusoidal hump. This particular level was caused by the articulated tipper vehicle with steel suspension in the laden condition. The next highest levels were caused by the two flat-top designs. As expected the control surface gave by far the lowest noise level. The mean averages of the noise level results across the whole vehicle sample show that the highest levels were more generally recorded next to the flat-top profiles.

The equivalent C-weighted results are shown in Figure 13(b). In this case the single highest level at a crossing speed of 25 km/h was recorded alongside the flat-top (straight ramp) hump. This result was very close to the maximum level obtained next to the flat-top (sinusoidal) hump. Notably, the highest level recorded alongside the control surface was much greater relative to the other profile results when compared with the A-weighted noise levels. This particular maximum result was obtained during tests with the articulated tipper vehicle with steel suspension in the unladen condition. It would seem likely that the high levels of low frequency noise causing the large differential between the A and C-weighted levels was caused by resonant vibrations of the tipper body caused by impacts between the body and the semi-trailer chassis.

ii At a typical speed for the type of profile

Figure 14(a) compares the maximum A-weighted noise levels during drive-bys with the light vehicle at typical crossing speeds over each of the test profiles. The noise levels alongside the control surface were often slightly higher for this comparison than those measured next to the test profiles. It should be noted though, that the typical drive-by speed for the control surface was much higher than for the hump profiles. For this vehicle type at least, drive-by noise would not be expected to increase as a result of installing any of the hump designs examined in this study. The range of different maximum noise levels reflects the range of crossing speeds associated with the different hump profiles. The highest level caused by any of the humps was that generated alongside the 5m round-top design as a result of the relatively high crossing speed for this profile. The C-weighted maximum noise levels (Figure 14(b)) showed a much smaller range of noise level differences despite the different drive-by speeds. This would indicate that C-weighted drive-by noise was less dependent on speed for this particular vehicle.

The equivalent results for the bus are shown in Figure 15. It was shown in Figure 6 that the maximum noise levels next to the profiles were not substantially different from those measured alongside the control surface at the same speed. When the results at typical crossing speeds are compared, the maximum drive-by noise levels alongside the hump profiles were lower than the drive-by noise beside the control surface. For this vehicle the hump profile causing most noise was the flat-top (straight ramp) hump. This profile also gave the highest C-weighted noise level of all the humps, although the range of C-weighted noise levels was smaller. Noise levels were lower for the non-standard sinusoidal designs relative to their standard equivalents.

Figure 16(a) compares the maximum and mean noise levels at typical crossing speeds for the combined commercial vehicle group. The two flat-top profiles caused the greatest maximum and mean levels of A-weighted noise. The two round-top profiles gave maximum levels that were similar to each other, and the lowest maximum results were measured alongside the sinusoidal profile. The round-top and sinusoidal profiles all gave similar mean levels. The figure indicates that there was little difference between the mean noise levels obtained for the control surface and the hump profiles. The typical drive-by speed was, of course, much higher for the control surface than for the humps. The rankings of the maximum and mean C-weighted noise levels were very similar to the A-weighted results for this vehicle group.

4.3.2 Ground-borne vibration alongside different hump profiles

i At a reference speed of 25 km/h

The maximum vibration level recorded across the whole vehicle sample during drive-bys at the 25 km/h reference speed was measured next to the flat-top (straight ramp) hump (Figure 13(c)). The second highest level occurred next to the flat-top profile (sinusoidal ramp). The 3.7m sinusoidal and 5m round-top humps gave the lowest levels of all the humps at this speed. The highest mean vibration level across the vehicle sample was also alongside the flat-top (straight ramp) hump. The second highest mean level occurred next to the 3.7m round-top. Again, the lowest level of all the humps were given by the 3.7m sinusoidal and 5m round-top profiles.

ii At a speed typical for the type of road profile

Figure 14(c) shows the vibration levels for the light vehicle crossing each profile at a typical speed. The range of vibration levels was very small. However, the highest levels were recorded alongside the round-top profiles. The lowest level was measured alongside the flat-top (straight ramp) profile.

The equivalent results for the bus are shown in Figure 15(c). In this case the highest level was given by the flat-top (straight ramp) profile and the lowest levels by the flat-top (sinusoidal ramp) and 3.7m round-top profiles. The vibration generated alongside the control surface at the typical drive-by speed was third in the ranking.

Figure 16(c) compares the maximum and mean vibration levels at typical crossing speeds for the combined commercial vehicle group. The flat-top (straight ramp) profile caused the greatest maximum and mean vibration levels. The second highest levels, relative to the other humps, were caused by the flat-top (sinusoidal ramp) hump. Compared with the results from the hump profiles, the control surface gave relatively high levels. It should be remembered though, that the assumed drive-by speed for this surface was much higher than for the hump profiles. In addition, there was some cracking of the surface in the vicinity of the measurement point which produced an uneven surface which may have contributed to the higher than expected vibration levels. The maximum and mean levels alongside the sinusoidal and round-top humps were similar.

5 Prediction of vibration at other sites

5.1 Predictions for different soil conditions

Previous studies have established that the shear modulus of the ground appears to be 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 on rock little vibration is generated (Watts, 1992)). It is therefore essential to make corrections for ground conditions when extrapolating from measurements on the test track where the underlying subsoil is relatively firm to other sites where the soil conditions are significantly different. This 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. This led to the calculation of ground scaling factors for common soil types.

Table 4 shows the ground scaling factors based on the original experiment (Watts, 1989) and the modified scaling factors *, t'*, that needs to be applied to the results obtained on the TRL test track (Central Area) in order to predict vibration levels on different soils.

Table 4 Ground scaling factors and power coefficients for attenuation

	Ground scaling factor		
Ground type	*Original*	*Modified*	*Power coefficient for attenuation*
Alluvium	7.07	4.40	-0.79
Peat	3.84	2.39	-1.19
London clay	3.10	1.93	-1.06
Sand/Gravel	0.94	0.58	-0.74
Boulder clay	0.43	0.27	-0.93
Chalk rock	0.10	0.06	-1.08

Applying these scaling factors to the results for the different profiles it has been shown (Watts, Harris and Layfield, 1997) that the predicted PPV at a building foundation, PPV_{site}, is given by:

$$PPV_{site} = PPV_{track} .t'.(r/6)^{x} \qquad (1)$$

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. Table 4 also lists the power coefficients needed for this calculation by soil type.

For each hump or cushion tested, equation (1) 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 level PPV_{site} this minimum distance is given by rearranging equation (1):

$$r_{min} = 6 \,.\, [\, PPV_{site} / (PPV_{track} .t')]^{1/x} \qquad (2)$$

The maximum vibration levels produced in the present tests were approximately 70% of the levels recorded in previous tests (Watts, Harris and Layfield, 1997) for the 3.7m long round top and 7.8m long flat-topped humps of comparable height. A smaller range of vehicles was used in the present test and in particular the vehicle that produced the highest levels in the previous tests was not available for the present study. The ‘worst case’ conditions are most appropriate for setting guide minimum distances and for this reason the peak vibration levels were increased in making these calculations. The approach used involved basing the multiplying factor on comparisons of the peak vibration levels for the 8m long flat-topped hump with straight ramps since this had a very similar height in both studies (73mm in the previous study and 75mm in the present study). In this case the PPV value was 1.399 higher in the previous study than in the present study. This multiplying factor was applied to the maximum PPV values obtained in the present study (given in Tables B3 and B4) and used in the calculation of minimum distances for various ground conditions.

The results of the calculations of minimum distances for various ground conditions are given in Section 5.2 below.

5.2 Minimum distances to nearest dwelling

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. A review of the literature has been carried out as part of the previous study (Watts, Harris and Layfield, 1997). Guide PPV threshold values of 0.3mm, 1, 3 and 19mm/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. Using a similar approach in the present study, equation 2 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 across the sample of vehicles tested in this study at the typical mean crossing speed were used for each profile.

For each profile the minimum distances are listed in Tables B1 to B4 in Appendix B and are shown in graphical form in Figure 17(a) to (e). It can be seen that minimum distances for the complaint threshold range up to 12m and for perception threshold up to 53m. In the case of the profile causing the highest level of vibration, even very minor fatigue damage is unlikely to occur unless the profile is placed less than 3m from the nearest foundation on soft soils.

It can be seen that greatest care should be exercised in locating the flat-top humps as they produced the highest peak vibration levels and consequently need to be positioned at the greatest distance from dwellings.

The round-top and sinusoidal humps produced very similar peak vibration levels and could be positioned at approximately half the distance of the flat-top humps on alluvial soils.

6 Summary and discussion

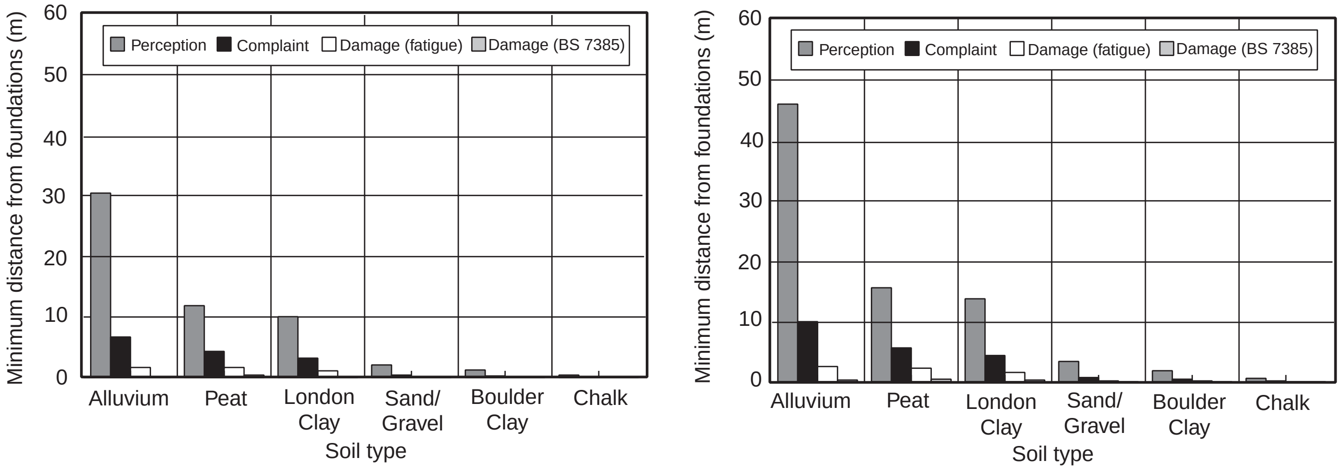
Noise and ground-borne vibration levels generated by a wide range of vehicle types crossing a selection of standard and non-standard road hump designs have been measured under controlled conditions on the TRL test track. The vehicles tested were: heavy commercial vehicles with different suspension types (tested laden and unladen), a double decker bus, and a passenger car. The five profiles used in the trials included three profiles not commonly used in Great Britain: a 3.7m long hump with a sinusoidal profile, a 5m long round-top hump, and an 8m long flat-top hump with sinusoidal ramps. Two frequently used ‘standard’ designs were included for comparison: a 3.7m long round-top hump and an 8m long flat-top hump with straight ramps (gradient 1:13). All the humps were 75mm high and were constructed on the TRL test track. The influence of profile shape and vehicle type on noise and vibration generation have been examined.

In the case of vehicle generated vibration the data has been used to predict likely maximum levels of ground-borne vibration alongside each profile design for a range of ground conditions. This has enabled the calculation of guide values for the minimum distances between road humps and cushions and the nearest dwelling to avoid different types of impact ranging from perception to damage to buildings. The main findings are summarised and discussed below.

6.1 Effects of profile shape and dimensions

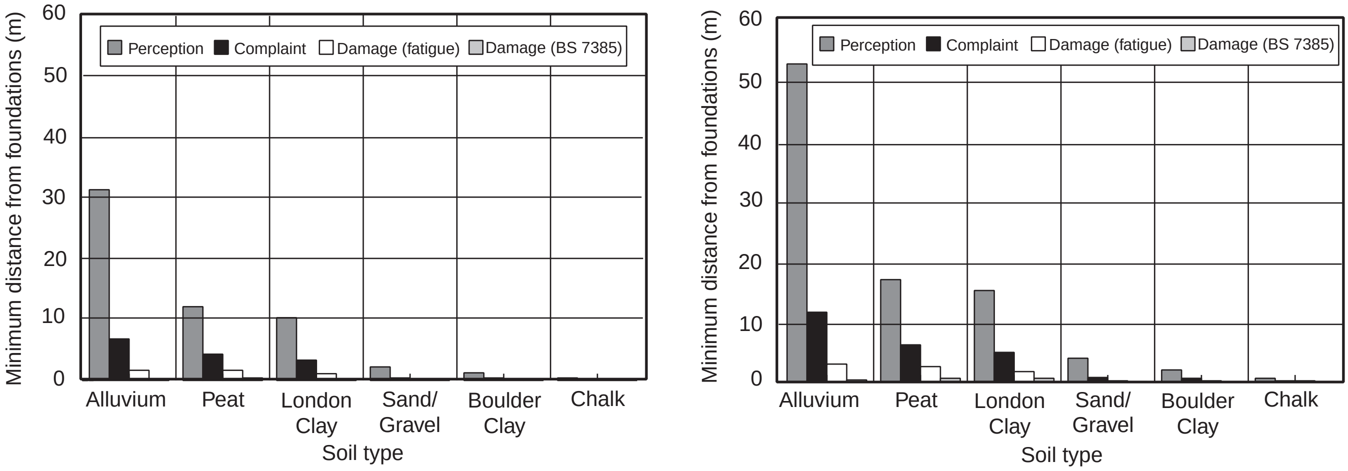
6.1.1 Noise

Comparing A-weighted noise levels generated alongside the profiles at typical crossing speeds for the light vehicles showed that the highest noise level occurred alongside a 5m round-top profile. There was no particular distinction between the results for standard and sinusoidal designs for either flat-top or round-top humps.



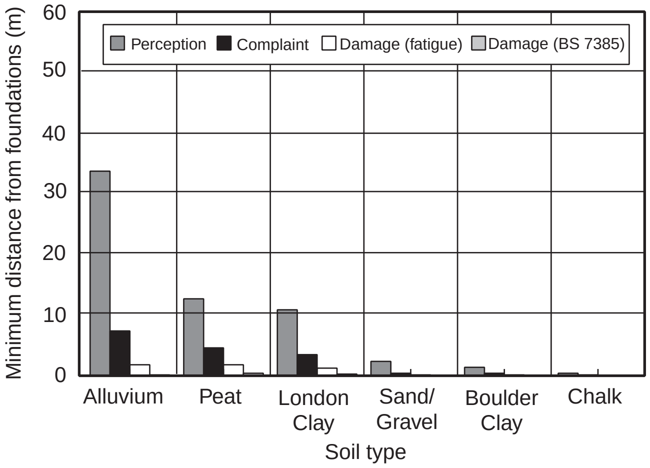
(a) Sinusoidal 3.7m hump

(d) Flat-top (sinusoidal ramps) hump



(b) Round-top 3.7m hump

(e) Flat-top (straight ramps) hump



(c) Round-top 5.0m hump

Figure 17 Predicted minimum distances between road profiles and dwellings to avoid vibration exposure

For the bus, the highest noise levels were obtained alongside the flat-top hump with straight ramps. The result for the flat-top hump with sinusoidal ramps was 4 dB(A) less. The noise level alongside the 3.7m sinusoidal hump was 2.5 dB(A) less than the result for the 3.7m round-top design. Both round-top humps gave similar levels.

Overall, for the bus, the non-standard sinusoidal designs gave distinctly lower noise levels than their standard equivalent profiles. All of the profile designs gave lower noise levels than that recorded next to the control surface for which the vehicle speed was much higher. The pattern of relative C-weighted noise level results for the various profiles was very similar to the that observed for the A-weighted levels.

For the commercial vehicles, the highest single noise level across the vehicle sample was measured alongside the flat-top (straight ramp) hump (generated by the unladen articulated tipper vehicle with steel suspension). This result was 1.1 dB(A) greater than the second highest result recorded for the same vehicle alongside the flat-top (sinusoidal ramp) hump. The two highest *mean* noise levels across the sample of commercial vehicle types were obtained for the flat-top humps. The maximum result obtained alongside the 3.7m round-top hump was 1.5 dB(A) higher than the maximum level obtained for the 3.7m sinusoidal hump. The mean noise levels across the commercial vehicle sample for these two profiles were equivalent. The 5m round-top gave a higher maximum level than the 3.7m humps but the mean noise level result was approximately equivalent.

Across the commercial vehicle group tested the results indicate that the sinusoidal designs typically caused similar mean noise levels as the flat-top (straight ramp) or round-top equivalents. However, the maximum levels tended to be slightly lower for the non-standard sinusoidal designs. The 5m round-top design did not show any advantage over the 3.7m round-top with respect to noise generation. Noise levels recorded alongside the flat-top humps were distinctly higher than those next to the other designs. This result agrees with the findings of earlier studies (Abbott, Tyler and Layfield, 1995). The mean noise levels obtained for the flat-top humps were approximately equivalent to the mean level obtained for the control surface at the typical crossing speeds. The maximum noise levels recorded alongside the humps were, however, much higher. The pattern of relative C-weighted noise level results for the various profiles was similar to the pattern obtained for the A-weighted results.

6.1.2 Ground-borne vibration

The levels of ground-borne vibration generated alongside the humps at typical crossing speeds have been compared. For the light vehicle there were generally no particularly distinct differences between the results obtained alongside the different profiles. The vibration levels were very low relative to those obtained for the larger vehicles.

For the bus, the highest vibration level result (relative to the other profiles) was obtained for the flat-top (straight ramp). The result for the flat-top (sinusoidal ramp) was nearly 0.9mm/s PPV less, approximately equivalent to the levels obtained for the round-top profiles. The vibration level recorded alongside the 3.7m sinusoidal hump was greater than the result obtained for the 3.7m round-top design. The result for the 5m round-top was slightly greater than the that for the 3.7m round-top.

For the commercial vehicles tested the highest mean and maximum ground-borne vibration levels occurred alongside the flat-top (straight ramp) hump. The flat-topped (sinusoidal ramp) hump gave slightly lower levels. The vibration levels recorded alongside the round-top and sinusoidal humps were very similar and significantly lower than the levels obtained alongside the flat-topped humps.

6.2 Effects of vehicle type and load

6.2.1 Noise

As expected, the levels of noise measured alongside the humps were lowest for the light vehicle. At the typical crossing speeds noise levels measured next to the profiles were within the range 63 - 68.7 dB(A). Noise levels for the bus were within the range 72.9 - 77 dB(A). In the case of the commercial vehicle group, maximum noise levels were measured in the range 82.4 - 89 dB(A). Mean results for the commercial vehicle sample were between 77.5 to 79.7 for the different profiles compared with 79.5 for the control surface. As discussed in Section 2.2 this indicates that significant increases only occur with certain commercial vehicle types. For the sample of commercial vehicles investigated during this study it was the articulated tipper vehicle with steel suspension that generated particularly high noise levels passing over the profiles. The other commercial vehicles generally generated lower levels of noise alongside the profiles than alongside the control surface, given the difference in the typical crossing speeds.

As established in the earlier study (Abbott, Taylor and Layfield, 1997) suspension type is clearly an important factor in the generation of body noise when commercial vehicles travel over vertical deflections. In this study equivalent air and steel suspended vehicles were directly compared to quantify the difference in noise generation. Noise levels generated during drive-bys at 25 km/h by the unladen articulated tipper vehicle with steel suspension were about 3 - 8 dB(A) higher than the corresponding noise levels generated alongside the profiles by the equivalent air suspended vehicle. In the laden condition the steel suspended vehicle generated noise levels between 6 and 15 dB(A) higher than those caused by the air suspended vehicle. These results show that noise levels were consistently higher for the steel suspended vehicle whether laden or unladen.

Comparisons were also made of the noise generated by the air and steel suspended vehicles under laden and unladen conditions. When the air suspended vehicle was unladen the noise levels measured next to the various profiles were about 3 - 10 dB(A) noisier. However, it has been noted that these differences could not entirely be attributed to the effect of load, as tyre/road noise was increased when the vehicle was tested in the unladen state due to the wet conditions. For the steel suspended vehicle the equivalent increases were about 0 - 5 dB(A) except for the 3.7m sinusoidal profile which gave a large decrease in noise level when the vehicle was unladen. These results were generally consistent with the results of the previous test track study (Abbott, Tyler and Layfield, 1995).

6.2.2 Ground-borne vibration

Levels of ground-borne vibration generated by the light vehicle measured alongside the humps were just above background levels. At the typical crossing speeds the vibration levels measured next to the profiles did not exceed 0.07mm/s PPV. Vibration levels for the bus travelling over the profiles were within the range 0.144 - 0.235mm/s PPV. For the commercial vehicle group, maximum vibration levels noise levels were higher, in the range 0.183 - 0.293 at the typical crossing speeds next to the profiles. Mean results across the commercial vehicle sample ranged from 0.142 to 0.198 mm/s PPV. The difference in the maximum and mean ranges demonstrates the range of vibration levels generated by different commercial vehicle types. As for the noise assessments, it was the articulated tipper vehicle with steel suspension that generated the highest vibration levels passing over the profiles.

It has been shown in the earlier study (Watts, Harris and Layfield, 1997) that suspension type was an important factor in the generation of ground-borne vibration when commercial vehicles travel over vertical deflections. Vibration levels generated during drive-bys at 25 km/h by the unladen articulated tipper vehicle with steel suspension were between approximately 0 and 0.08mm/s PPV lower than the corresponding noise levels generated alongside the profiles by the equivalent air suspended vehicle. In the laden condition the steel suspended vehicle generated vibration levels between 0.01 and 0.06mm/s PPV lower than those caused by the air suspended vehicle. For the vehicles tested in this study it would appear, therefore, that vibration levels were not substantially different for equivalent vehicles fitted with either air or steel suspension, whether laden or unladen.

Comparisons were also made of the vibration generated by the air and steel suspended vehicles when in laden and unladen conditions. When the air suspended vehicle was unladen the vibration levels measured next to the various profiles were between approximately 0.01 - 0.06mm/s greater (except for the 3.7m round-top hump which gave a decrease in level). For the steel suspended vehicle the increases were between approximately 0 - 0.16mm/s PPV. The influence of load was therefore generally greater for the steel suspended vehicle.

6.3 Profile selection

The results of this study can indicate which of the 75mm high hump designs would be expected to cause the lowest noise and vibration disturbances. However, care needs to be taken in interpreting the results since the number of vehicles tested was limited although efforts were made to select vehicles that were representative of the fleet.

For the light vehicle tested, noise and vibration levels were relatively low and there was no firm evidence that any of the humps would produce substantially different levels in practice than the others. However, for the commercial vehicles it did appear that the 75mm high flat-top humps produced substantially higher noise and vibration levels than the other designs. This was especially evident in the case of the flat-top hump with straight ramps (gradient 1:13). Of the *non*-flat-top designs the sinusoidal profile appeared to reduce the maximum noise level for the commercial vehicles relative to the results obtained for the round-top profiles. In the case of the bus tested there was evidence that the flat-top (sinusoidal ramp) hump gave lower noise levels than the flat-top (straight ramp) hump and the round-top designs.

In practice, most roads carry a mixture of vehicle types and by avoiding the flat-top designs the very highest levels of noise and vibration that residents will be exposed to should be minimised. Such a strategy should also produce benefits on roads with relatively few heavy vehicles since a recent study (report currently in preparation) has indicated that even infrequent high noise levels from commercial vehicles passing over vertical deflections can cause annoyance to local residents. When deciding on the appropriate hump profile, other factors as well as noise will need to be taken into account. The results of the measurements of passenger/rider discomfort at the hump profiles are reported in the 'companion' TRL Report TRL417 (Sayer *et al*, 1999).

6.4 Vibration exposure at sites with different soil conditions

Figure 17(a) to (e) can be used to guide decisions on the selection and siting of humps and cushions to avoid possible disturbance due to the generation of perceptible vibration in dwellings. It should be noted that only in unusual circumstances is it likely that there will be a risk of superficial building damage and there is no evidence that more serious structural damage could occur. At the high levels of vibration required to cause even this minor damage, occupants would probably find the vibrations intolerable and action to reduce vibration would probably need to be taken long before building damage was sustained.

In addition to careful hump and cushion selection and siting a further option to reduce vibration exposure is traffic management. Based on the results of the previous study in which a wider range of commercial vehicles was tested, it is likely that maximum vibration levels can be halved if vehicle weights are restricted to 7.5 tonnes (Watts, Harris and Layfield, 1997). A restriction on the times when HGVs can enter the controlled area may also alleviate the problem by reducing the duration of exposure.

It should be noted that the propagation of vibration in soils is complex and 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 reflection take place within the soil mass leading to lower rates of attenuation with distance than in an homogeneous soil mass. In addition the soil type may not fall conveniently within the categories for which data is available. In such cases it is recommended that measurements are carried out to verify these predictions. Any such measurements should only be carried out by persons skilled in vibration measurement and interpretation of the results. The maximum likely vibration levels at the nearest foundations can be gauged by driving a heavy test vehicle over a temporary profile laid in the road[3].

7 Conclusions

The following conclusions can be drawn from the study based on typical mean crossing speed data for each profile tested:

7.1 Noise

1 For the light vehicle tested the noise levels generated alongside the various hump profiles were less than that measured next to the control surface. The differences in noise between hump designs were relatively small and there is no firm evidence that in practice any noticeable difference in noise would occur for any of the hump designs tested.

2 For the double decker bus it was found that the non-standard sinusoidal profiles gave distinctly lower noise levels than their standard equivalents. The highest levels were recorded alongside the flat-top (straight ramp) hump. The pattern of relative C-weighted noise level results for the various profiles was very similar to that obtained with A-weighted levels.

3 The highest noise levels at typical crossing speeds for the commercial vehicle group were recorded alongside the flat-top humps. The maximum noise levels were slightly lower for the non-standard sinusoidal designs than their standard equivalents. However, across all the commercial vehicles tested, the sinusoidal designs typically caused similar *mean* vehicle generated noise levels to those measured alongside their standard equivalents. The 5m round-top hump did not show any particular advantage over the 3.7m round-top with respect to noise generation. The overall pattern of relative C-weighted noise level results for the various profiles was similar to the results obtained using A-weighted levels.

4 Noise levels generated during drive-bys at 25 km/h by the unladen articulated tipper vehicle with steel suspension were between approximately 3 and 8 dB(A) higher than the corresponding noise levels generated alongside the profiles by the equivalent air suspended vehicle. In the laden condition the steel suspended vehicle generated noise levels between 6 and 15 dB(A) higher than those caused by the air suspended vehicle. These results generally confirm the results of the previous test track study.

5 When the air suspended vehicle was unladen the noise levels measured during drive-bys at 25 km/h next to the various profiles were between approximately 3 - 10 dB(A) noisier than when the vehicle was laden. Although body noise was dominant during the drive-bys, these increases may have been influenced by the wet conditions during these particular tests. Noise levels generated by the equivalent steel suspended vehicle were between approximately 0 - 5 dB(A) greater when the vehicle was unladen (except for the 3.7m sinusoidal profile which gave a large decrease in noise level when the vehicle was unladen). These results were similar to those obtained during the previous track study.

7.2 Vibration

6 For the light vehicle the levels of ground-borne vibration were only marginally higher than background, and much lower than the results obtained for the heavier vehicles. Generally, there were no distinct differences between the results obtained alongside the different profiles.

7 For the double decker bus the highest vibration level at typical crossing speeds was caused by the flat-top (straight ramp) profile. The equivalent result for the flat-top (sinusoidal ramp) profile was nearly 0.9mm/s PPV less. The 3.7m sinusoidal profile gave a higher level than its round-top equivalent.

8 The highest maximum and mean vibration levels (relative to the other profiles) at typical crossing speeds for the commercial vehicle group were recorded alongside the flat-top humps. The non-standard, flat-top (sinusoidal ramp) hump caused lower ground-borne vibration levels than its standard equivalent. The sinusoidal-top and round-top humps gave similar vibration results which were significantly lower than those given by the flat-top humps.

9 Vibration levels generated by equivalent commercial vehicles fitted with air suspension and steel suspension were compared for drive-bys over the humps at 25 km/h in both laden and unladen conditions. The results showed that, in general, vibration levels caused by the two vehicles were not substantially different.

10 The equivalent air suspended and steel suspended commercial vehicles both caused higher vibration levels when travelling over the hump profiles in the unladen condition. However, the influence of load on vibration level was typically slightly greater for the steel suspended vehicle.

11 The minimum distances to avoid different levels of vibration exposure have been calculated for various underlying soil types. At the level of human perception (peak vertical vibration level of 0.3mm/s) the risk of complaints would be low. Predictions of minimum distances to avoid perception of vibration ranged up to 53m for the flat-top hump with straight ramps at a site with the softest soil type. For the sinusoidal-top and round-top humps on the same soil type the predictions were just over half this distance. On firmer soils, the minimum distances were much smaller. Minimum distances were also calculated for the higher level of 1mm/s. Above this level complaints would be expected. On this criteria minimum distances ranged up to 12m for the softest soil type. With regard to potential damage to buildings it is very unlikely that even superficial damage could be caused by the installation of humps and cushions.

12 The propagation of vibration in soils is complex and it is quite possible for higher levels than those predicted to be encountered especially if the soil is layered so that significant reflection takes place within the soil mass. The predicted minimum distance values are for guidance only and in cases of doubt it is recommended that measurements are carried out with a test vehicle and temporary profile to verify these predictions. Any such measurements should only be carried out by persons skilled in vibration measurement and interpretation of the results.

7.3 Profile selection

13 The results of this study show that for commercial vehicles the 75mm high flat-top humps produced substantially higher noise and vibration levels than the other designs tested. As most roads carry a mixture of vehicle types the very highest levels of noise and vibration should be minimised by avoiding the use of flat-top designs. When deciding on the appropriate hump profile, other factors as well as noise and vibration will need to be taken into account. The results of the measurements of passenger/rider discomfort at the hump profiles are reported in the ‘companion’ TRL Report TRL417 (Sayer *et al,* 1999).

8 Acknowledgements

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Notes

[1] Commercial vehicle body noise is caused by impacts between parts of the vehicle body or between components of steel suspension systems. This type of noise can occur when heavy vehicles travel over a surface irregularity which causes vertical forces to be transmitted through the vehicle body via the suspension.

[2] A-weighting gives the noise measuring instrument a frequency response approximately equivalent to that of the human ear. For many noise assessment purposes the dB(A) scale has been found to correlate well with the subjective perception of noise. C-weighting employs less weighting at low frequencies than A-weighting and is, therefore, often used where the sound source contains a high proportion of low frequency noise.

[3] The Transport Research Laboratory has developed an appropriate test procedure for this type of assessment.

Appendix A: Photographs

Plate 1 Profile P1, sinusoidal hump, 3.7m long

Plate 2 Profile P2, round-top hump, 3.7m long

Plate 3 Profile P3, round-top hump, 5.0m long

Plate 4 Profile P4, flat-top hump with sinusoidal ramps

Plate 5 Profile P5, flat-top hump with straight ramps

Plate 8 Test vehicle 1 (tractor and tipper trailer, air suspension — laden)

Plate 9 Test vehicle 2 (tractor and tipper trailer, air suspension — unladen)

Plate 10 Test vehicle 3 (tractor and tipper trailer, steel suspension — laden)

Plate 11 Test vehicle 4 (tractor and tipper trailer, steel suspension — unladen)

Plate 12 Test vehicle 5 (dropside rigid truck, steel suspension — unladen)

Plate 13 Test vehicle 6 (double deck bus, air suspension)

Plate 14 Test vehicle 7 (passenger car)

Appendix B: Tables

Table B1 Maximum and mean noise and ground-borne vibration levels for each hump profile (all test vehicles — 25 km/h)

	PPV (mm/s)		L_{Amax}		L_{Cmax}	
Profile description	*Max*	*Mean*	*Max*	*Mean*	*Max*	*Mean*
Sinusoidal 3.7m	$0.256^{*}_{(4)}$	$0.192_{(4)}$	$90.2_{(1)}$	$77.4_{(3)}$	$95.5_{(3)}$	$86.4_{(3)}$
Round-top 3.7m	$0.324_{(3)}$	$0.223_{(2)}$	$83.5_{(5)}$	$76.2_{(4)}$	$91.0_{(5)}$	$85.1_{(4)}$
Round-top 5.0m	$0.249_{(5)}$	$0.181_{(5)}$	$83.8_{(4)}$	$74.9_{(5)}$	$90.6_{(6)}$	$84.0_{(6)}$
Flat-top (sinusoidal ramp)	$0.329_{(2)}$	$0.198_{(3)}$	$88.7_{(2)}$	$80.1_{(1)}$	$96.1_{(2)}$	$87.3_{(2)}$
Flat-top (straight ramp)	$0.397_{(1)}$	$0.269_{(1)}$	$88.4_{(3)}$	$79.3_{(2)}$	$96.5_{(1)}$	$87.6_{(1)}$
Control surface	$0.178_{(6)}$	$0.120_{(6)}$	$78.0_{(6)}$	$73.5_{(6)}$	$93.5_{(4)}$	$84.1_{(5)}$

[*] *The numbers in brackets denote the rank order of each result relative to the highest level*

Table B2 Noise and ground-borne vibration levels for each hump profile (light vehicle only — typical mean crossing speed)

Profile description	*PPV (mm/s)*	L_{Amax}	L_{Cmax}
Sinusoidal 3.7m	$0.056^{*}_{(4)}$	$65.1_{(3)}$	$81.9_{(2)}$
Round-top 3.7m	$0.070_{(1)}$	$64.8_{(4)}$	$82.0_{(1)}$
Round-top 5.0m	$0.067_{(2)}$	$68.7_{(2)}$	$80.3_{(6)}$
Flat-top (sinusoidal ramp)	$0.061_{(3)}$	$63.8_{(5)}$	$81.5_{(3)}$
Flat-top (straight ramp)	$0.051_{(5)}$	$63.0_{(6)}$	$81.3_{(4)}$
Control surface[+]	$0.049_{(6)}$	$71.5_{(1)}$	$81.1_{(5)}$

[*] *The numbers in brackets denote the rank order of each result relative to the highest level*

[+] *The level surface was only tested at a maximum speed of 45 km/h. The mean crossing speed was 48 km/h*

Table B3 Noise and ground-borne vibration levels for each hump profile (bus only — typical mean crossing speed)

Profile description	*PPV (mm/s)*	L_{Amax}	L_{Cmax}
Sinusoidal 3.7m	$0.189^{*}_{(2)}$	$72.9_{(6)}$	$80.0_{(5)}$
Round-top 3.7m	$0.144_{(6)}$	$75.4_{(3)}$	$81.3_{(3)}$
Round-top 5.0m	$0.155_{(4)}$	$75.1_{(4)}$	$80.6_{(4)}$
Flat-top (sinusoidal ramp)	$0.147_{(5)}$	$73.0_{(5)}$	$79.2_{(6)}$
Flat-top (straight ramp)	$0.235_{(1)}$	$77.0_{(2)}$	$81.6_{(2)}$
Control surface	$0.157_{(3)}$	$78.2_{(1)}$	$83.5_{(1)}$

[*] *The numbers in brackets denote the rank order of each result relative to the highest level*

Table B4 Maximum and mean noise and ground-borne vibration levels for each hump profile (commercial vehicles — typical mean crossing speed).

	PPV (mm/s)		L_{Amax}		L_{Cmax}	
Profile description	*Max*	*Mean*	*Max*	*Mean*	*Max*	*Mean*
Sinusoidal 3.7m	$0.183^{*}_{(6)}$	$0.142_{(6)}$	$82.4_{(5)}$	$77.6_{(4)}$	$88.5_{(6)}$	$85.9_{(4)}$
Round-top 3.7m	$0.194_{(4)}$	$0.151_{(4)}$	$83.9_{(4)}$	$77.5_{(5)}$	$90.0_{(4)}$	$85.3_{(5)}$
Round-top 5.0m	$0.185_{(5)}$	$0.143_{(5)}$	$84.8_{(3)}$	$77.5_{(5)}$	$90.0_{(4)}$	$84.6_{(6)}$
Flat-top (sinusoidal ramp)	$0.261_{(3)}$	$0.170_{(3)}$	$87.9_{(2)}$	$79.7_{(1)}$	$94.1_{(2)}$	$87.2_{(3)}$
Flat-top (straight ramp)	$0.293_{(1)}$	$0.198_{(1)}$	$89.0_{(1)}$	$79.0_{(3)}$	$96.0_{(1)}$	$87.5_{(2)}$
Control surface	$0.265_{(2)}$	$0.187_{(2)}$	$82.3_{(6)}$	$79.5_{(2)}$	$92.8_{(3)}$	$88.2_{(1)}$

[*] *The numbers in brackets denote the rank order of each result relative to the highest level*

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

Table B5 Sinusoidal 3.7m hump

Minimum distance of road profile from foundations (m)*

Level of vibration exposure	Soil type					
	Alluvium	*Peat*	*London clay*	*Sand/ gravel*	*Boulder clay*	*Chalk rock*
Perception	31	12	10	2	1	<1
Complaint	7	4	3	<1	<1	<1
Damage (Fatigue)	2	2	1	<1	<1	<1
Damage (BS7385)	<1	<1	<1	<1	<1	<1

* *Calculated distance is from the nearest wheel track over the profile to building foundations*

Table B6 Round-top 3.7m hump

Minimum distance of road profile from foundations (m)*

Level of vibration exposure	Soil type					
	Alluvium	*Peat*	*London clay*	*Sand/ gravel*	*Boulder clay*	*Chalk rock*
Perception	32	12	10	2	1	<1
Complaint	7	4	3	<1	<1	<1
Damage (Fatigue)	2	2	1	<1	<1	<1
Damage (BS7385)	<1	<1	<1	<1	<1	<1

* *Calculated distance is from the nearest wheel track over the profile to building foundations*

Table B7 Round-top 5.0m hump

Minimum distance of road profile from foundations (m)*

Level of vibration exposure	Soil type					
	Alluvium	*Peat*	*London clay*	*Sand/ gravel*	*Boulder clay*	*Chalk rock*
Perception	34	13	11	2	1	<1
Complaint	7	5	4	<1	<1	<1
Damage (Fatigue)	2	2	1	<1	<1	<1
Damage (BS7385)	<1	<1	<1	<1	<1	<1

Table B8 Flat-top (sinusoidal ramps) hump

Minimum distance of road profile from foundations (m)*

Level of vibration exposure	Soil type					
	Alluvium	*Peat*	*London clay*	*Sand/ gravel*	*Boulder clay*	*Chalk rock*
Perception	46	16	14	3	2	1
Complaint	10	6	4	1	<1	<1
Damage (Fatigue)	2	2	2	<1	<1	<1
Damage (BS7385)	<1	<1	<1	<1	<1	<1

* *Calculated distance is from the nearest wheel track over the profile to building foundations*

Table B9 Flat-top (straight ramps) hump

Minimum distance of road profile from foundations (m)*

Level of vibration exposure	Soil type					
	Alluvium	*Peat*	*London clay*	*Sand/ gravel*	*Boulder clay*	*Chalk rock*
Perception	53	17	15	4	2	1
Complaint	12	6	5	1	1	<1
Damage (Fatigue)	3	2	2	<1	<1	<1
Damage (BS7385)	<1	1	<1	<1	<1	<1

* *Calculated distance is from the nearest wheel track over the profile to building foundations*

Abstract

Work on the development of speed reducing road humps carried out at TRL resulted in a circular (round-top) hump profile which has been successfully used on roads in many countries. Since the 1980's the regulations governing the use of road humps in England and Wales have been gradually relaxed to allow greater flexibility in the shape of humps so as to include flat-top humps, raised junctions and speed cushions. The current regulations do not specify an exact hump profile providing the humps are between 25 mm and 100 mm in height, at least 900 mm long and with no vertical face exceeding 6mm. Humps with a sinusoidal profile have been reported as being more comfortable for cyclists, and possibly also for car drivers, but there has been little information as to the relative difference between the profiles regarding their impact on noise and ground-borne vibration levels.

In order to improve the advice available to local highway authorities, the Charging and Local Transport Division of DETR commissioned TRL to undertake a comparative evaluation in terms of passenger/rider discomfort, vertical acceleration, vehicle generated noise and ground-borne vibration of a number of humps, all 75 mm high, but with different profiles. The five profiles used in the trials included three non-standard profiles: a 3.7m long hump with a sinusoidal profile, a 5m long round-top hump, and an 8m long flat-top hump with sinusoidal ramps. Two frequently used hump profiles were included for comparison: a 3.7m long round-top hump and an 8m long flat-top hump with straight ramps. All humps were installed on the TRL test track. This report gives details of the track trial at TRL and the results obtained from the measurements of noise and ground-borne vibration levels. The 'companion' TRL Report 417 (Sayer *et al*, 1999) gives details of the results of the measurements of passenger discomfort and peak vertical acceleration.

Related publications

TRL417	*Traffic calming: Passenger and rider discomfort at sinusoidal, round-top and flat-top humps — a track trial at TRL* by I A Sayer, D A Nicholls and R E Layfield. 1999 (price £35, code J)
TRL377	*Traffic calming - sinusoidal, 'H' and 'S' humps* by D C Webster and R E Layfield. 1998 (price £50, code L)
TRL312	*Traffic calming - speed cushion schemes* by R E Layfield and D I Parry. 1998 (price £35, code H)
TRL235	*Traffic calming: vehicle generated ground-borne vibration alongside speed control cushions and road humps* by G R Watts, G J Harris and R E Layfield. 1997 (price £35, code H)
TRL215	*Review of traffic calming schemes in 20 mph zones* by D C Webster and A M Mackie. 1996 (price £35, code H)
TRL186	*Traffic calming - road hump schemes using 75 mm high humps* by D C Webster and R E Layfield. 1996 (price £35, code H)
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