TRANSPORT RESEARCH LABORATORY

Traffic calming: Passenger and rider discomfort at sinusoidal, round-top and flat-top humps — a track trial at TRL

Prepared for Charging and Local Transport Division, Department of the Environment, Transport and the Regions

I A Sayer, D A Nicholls and R E Layfield

TRL REPORT 417

First Published 1999
ISSN 0968-4107

This report has been produced by the Transport Research Laboratory, under/as part of a Contract placed by the Department of the Environment, Transport and the Regions. Any views expressed are not necessarily those of the Department.

Transport Research Foundation Group of Companies

Transport Research Foundation (a company limited by guarantee) trading as Transport Research Laboratory. Registered in England, Number 3011746.

TRL Limited. Registered in England, Number 3142272.
Registered Offices: Old Wokingham Road, Crowthorne, Berkshire, RG45 6AU.

CONTENTS

Executive Summary

The original 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 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 round-top or flat-top humps but little information has been available as to the degree of difference between the profiles.

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 (P1), a 5m long round-top hump (P3), and an 8m long flat-top hump with sinusoidal ramps (P4). Two 'standard' profiles were included for comparison: a 3.7m long round-top hump (P2) and an 8m long flat-top hump with straight ramps (P5). All the humps were 75mm high.

This report gives details of the track trial at TRL and the results obtained from the measurements of passenger discomfort and peak vertical acceleration. A companion report, TRL Report TRL416 (Harris *et al*, 1999), gives details of the results of the measurements of vehicle noise and ground-borne vibration alongside the humps and provides estimates of the minimum distances between hump profiles and dwellings to avoid vibration exposure. It should be noted that the humps used in the trials were carefully constructed in concrete to examine differences in hump profiles. Many humps used on the public roads may be more severe in terms of their discomfort to road users due to a greater height, a steeper ramp gradient, the use of irregular materials such as setts, or the occurrence of discontinuities where the road hump meets the road surface.

The vehicles used in the study included bicycles, motorcycles, a motor cycle/side-car combination, cars, buses, goods vehicles and emergency service vehicles. The speed ranges selected for testing covered speeds likely to be found on the public roads (from 10 mph up to a maximum of 40 mph for cars and up to 30 mph for other motor vehicles). Most riders and drivers reported no vehicle handling problems when crossing the profiles at speeds within the range tested. However, concerns about severe discomfort, vehicle damage or vehicle handling precluded driving some vehicles (*e.g.* buses, heavy goods vehicles and emergency vehicles) over some hump profiles at the higher speeds. Cyclists rode over the humps at speeds in the range 10 to 20 mph.

For most of the vehicle types (cars, buses, goods vehicles and emergency service vehicles), two measures were used to evaluate the discomfort experienced by vehicle occupants: a subjective assessment of discomfort on a 0 to 6 scale made by one or more vehicle occupants; and a record of the peak upward vertical acceleration experienced by one vehicle occupant at a particular location in the vehicle. In previous studies these two measures have shown generally good correlation with each other. The results in the report are presented for each vehicle type. They are summarised below for each profile tested.

Sinusoidal hump, 75mm high, 3.7m long - (P1)

This hump profile gave less discomfort to cyclists than profile P2, the 'standard' 3.7m long round-top hump. However, the difference in discomfort was not large. There was a slight benefit in terms of discomfort to car passengers in the use of profile P1 compared to profile P2 but there was little, if any, benefit to motor cycle riders, bus passengers, commercial vehicle drivers, fire crew and ambulance passengers. It is likely that the speed reduction achieved by the use of the sinusoidal profile P1 on the public roads would be similar to that achieved by the round-top profile P2. The companion TRL Report TRL416 indicates that maximum noise and ground-borne vibration levels generated by the passage of heavy commercial vehicles are likely to be slightly less with P1, the sinusoidal hump than with P2, the 'standard' round-top hump. However, the results for the double-deck bus that was tested were less consistent with lower maximum noise levels, but higher ground-borne vibration levels, with profile P1 than with profile P2.

Depending on the method of hump construction used in hump schemes on the public roads, there may be extra difficulty/expense in constructing the sinusoidal profile rather than a round-top profile and this would need to be taken into account when deciding which hump profile was appropriate.

Flat-top hump with sinusoidal ramps, 75mm high, 6m plateau, 1m ramps - (P4)

There was little, if any, benefit in terms of discomfort to any of the riders and vehicle occupants in the use of profile P4 compared to the 'standard' flat-top hump with straight ramps, profile P5. It is likely that the speed reduction achieved by the use of profile P4 on the public roads would be similar to that achieved by profile P5. The companion TRL Report TRL416 indicates that maximum noise and ground-borne vibration levels generated by the passage of buses and heavy commercial vehicles are likely to be less with P4, the flat-top hump with sinusoidal ramps, than with P5, the 'standard' flat-top hump with straight ramps.

The flat-top hump profiles, P4 and P5, gave the most discomfort for cyclists. In order to reduce discomfort to cyclists, the results indicate that the use of flat-top hump profiles on routes used by substantial numbers of cyclists should be avoided, except at humped pedestrian crossings where a flat surface is required.

Round-top hump, 75mm high, 5m long - (P3)

This hump profile gave the lowest values of discomfort, throughout most of the speed range tested, to cyclists, motor cycle riders and car passengers. Also, it gave the lowest values of discomfort, at speeds of 10 to 15 mph, for bus passengers, fire crew and ambulance passengers.

The use of profile P3, the 5m long round-top hump, on the public roads rather than the more commonly used profiles P2, the 3.7m long round-top, and P5, the flat-top with straight ramps, would reduce discomfort for drivers, riders and passengers if travelling at similar speeds to those that occur in practice with humps of type P2 and P5. However, it is likely that car drivers on the public roads would increase speed to bring the discomfort experienced at profile P3 in line with that experienced at profiles P2 and P5. Mean crossing speeds for cars at profile P3 are therefore likely to be about 20 to 25 mph, compared to about 15 mph at profiles P2 and P5.

Profile P3 might be suitable for use where it was desired to control speeds to below 30 mph rather than to below 20 mph. Any benefit to passengers in buses and ambulances in terms of reduced discomfort would require bus and ambulance drivers to keep their speeds low rather than take advantage of the lower levels of discomfort to increase speed. The companion TRL Report TRL416 indicates that maximum noise and ground-borne vibration levels generated by the passage of buses and heavy commercial vehicles over the 5m long round-top profile P3 are likely to be similar to those generated over the 3.7m long round-top profile P2.

Round-top hump, 75mm high, 3.7m long - (P2) and Flat-top hump with straight ramps 75mm high, 6m plateau, 1m ramps - (P5)

The ‘standard’ 3.7m long round-top profile, P2, gave lower values of discomfort for cyclists, motor cycle riders and car passengers, throughout most of the speed range tested, than the ‘standard’ flat-top profile, P5. Profile P2 also generally gave lower values of discomfort than P5 for the motor cycle/side-car combination, bus passengers, commercial vehicle drivers, fire crew and ambulance passengers when travelling at speeds of 10 to 15 mph. However, at speeds above 15 mph, the round-top hump profile P2 generally gave similar or higher values of discomfort for these vehicle types than the flat-top hump profile P5.

Above 20 mph, the discomfort experienced by car occupants when travelling over profile P5, increased more rapidly with speed than that for profile P2. Thus the flat-top profile P5 might be more suitable than the round-top profile P2 at discouraging car drivers who might otherwise drive at these higher speeds. However, a general use of the flat-top hump profile P5 rather than the round-top profile P2 for controlling car speeds to below 20 mph, would increase discomfort for cyclists, and, at speeds below 15 mph, for passengers in buses and ambulances. The companion TRL Report TRL416 indicates that the use of the flat-top profile P5 rather than the round-top profile P2 would also increase the noise and ground-borne vibrations generated by the passage of buses and heavy commercial vehicles. On bus routes and routes commonly used by the emergency services and commercial traffic, other traffic calming measures, such as narrow speed cushions which generally give less discomfort and cause less delay than road humps, are possibly more appropriate.

The discomfort experienced by bus passengers substantially increased as speeds across the hump profiles increased from 15 to 20 mph. Driving buses on the public roads at speeds over 15 mph across sinusoidal, round-top or flat-top profiles of the types tested is likely to cause unnecessary discomfort to bus passengers. Bus operators should try to encourage drivers to cross such hump profiles at speeds of 15 mph or less to minimise discomfort. For some combinations of bus type and hump profile a steady speed of 15 mph might be appropriate along roads where road humps are present.

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 at a range of speeds. These experiments resulted in the circular profile 'round-top' hump of 12 feet long and 4 inches high (3.7 metres and 100 mm, see Figure 1). 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 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 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 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, 1996; Statutory Instrument 1999 No. 1025).

For a given speed, the passenger discomfort in buses (or other large vehicles) when travelling over humps is likely to be higher than that in cars. To compensate for this, buses tend to be driven slower over humps than cars (about 5 mph slower, on average, for 75 mm high humps). 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 lead 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

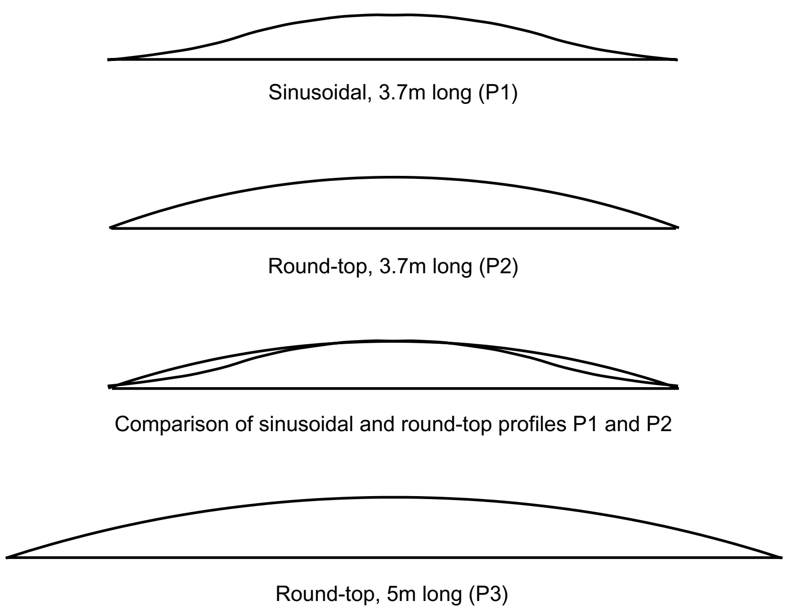


Figure 1 Sinusoidal and round-top hump profiles tested (height dimensions exaggerated)

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 (De Wit and Slop, 1984; De Wit, 1993; Lines and Castelijn, 1991; Lahrmann and Mathiasen, 1992; Moses, 1992). Several local highway authorities in England have used flat-top humps with sinusoidal shape ramps or with straight ramps ‘rolled over’ at the top to reduce the sharp angle between the ramp and plateau and give an approximate sinusoidal profile. Again, it is not clear what improvement there is, if any, in terms of passenger discomfort.

In Denmark, 100mm high round-top humps with a longer cross-section in the direction of travel (5 m) are recommended as speed reduction measures where crossing speeds for cars of 35 km/h (22 mph) are desired. This is about 10 km/h (6 mph) higher than for the standard, 100mm high, 3.7 m long round-top hump (Danish Road Directorate, 1991).

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 levels 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 preselected 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 and calculate minimum distances between the hump profiles and dwellings to avoid vibration exposure;

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 peak vertical acceleration and passenger/rider discomfort. The results of the measurements of vehicle noise and ground-borne vibration alongside the hump profiles are given in a companion report, TRL Report TRL416, (Harris *et al*, 1999).

2 Hump profiles and construction

2.1 Hump profile outlines and dimensions

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 (P1), a 5m long round-top hump (P3), and an 8m long flat-top hump with sinusoidal ramps (P4). Two ‘standard’ profiles were included for comparison: a 3.7m long round-top hump (P2) and an 8m long flat-top hump with straight ramps (P5). All the hump profiles were 75mm high.

Figure 1 shows the sinusoidal hump profile, P1 and the round-top hump profile, P2, both 3.7m long in the direction of travel. Differences between the sinusoidal and round-top profiles are shown by the diagram superimposing the P2 and P1 profiles. Figure 1 also shows the longer (5m) round-top hump profile, P3. Figure 2 shows the flat-top profile with sinusoidal ramps, P4, and the flat-top profile with straight ramps, P5. Differences between the ramp profiles are shown by the diagram superimposing the two ramp profiles. Photographs of the humps are shown in Plates 1 to 5, Appendix A. The dimensions of the profiles are given in Table 1.

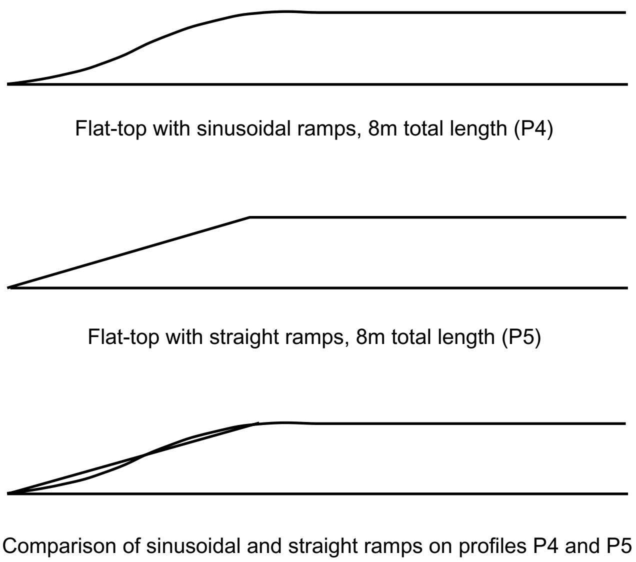


Figure 2 Flat-top hump profiles tested (height dimensions exaggerated)

Table 1 Hump profile dimensions

Description of profile	Length[1] (m)	Max height (mm)	Plateau length (m)	On/off ramp gradient	Width[2] (m)	Tapered edge gradient
P1 Sinusoidal	3.7	75	n/a	n/a	3.4	1:4
P2 Round-top	3.7	75	n/a	n/a	3.4	1:4
P3 Round-top	5.0	75	n/a	n/a	3.4	1:4
P4 Flat-top, sinusoidal ramps	8.0	75	6.0	n/a	3.4	1:4
P5 Flat-top, straight ramps	8.0	75	6.0	1:13	3.4	1:4

[1] In direction of travel
[2] Excluding tapered-edges; n/a not applicable

2.2 Hump construction

The five hump profiles were positioned in lanes in the Central Area (approximately 270m in diameter) of the TRL test track. The location of the hump profiles ensured adequate space for all the vehicles tested to reach the required speed over the humps and brake safely.

During the hump construction, care was taken to achieve a uniform and precise profile. The hump profiles were constructed of concrete (see Appendix A, Plates 6 and 7). Each hump was about half a road width (3.4m) wide, excluding the tapered edges. 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 used to line the cut out areas. These were filled with ready mixed concrete, compacted, using internal vibrators and tamped into place using a heavy wooden straight edge. The humps that were longer than 3.7 metres (P3, P4 and P5) were cast in two sections.

A membrane was used to help cure the concrete. To improve surface skid resistance, vehicle running surfaces and end ramps received a light transverse brushing whilst soft. The hump profiles joined the track surface in a smooth manner with no noticeable upstand at the junction. The humps were marked in a similar manner to humps on the public roads, with two triangular road markings painted on the vehicle approach ramps.

The humps constructed in this trial were designed to examine the effects of differences in the hump profiles of 75 mm high humps and, as has been stated above, were carefully constructed in concrete with a smooth transition between the hump and the road surface. It should be noted that many humps used on the public roads may be more severe in terms of their effect on road users due to a greater height (100 mm maximum), a steeper ramp gradient, the use of irregular materials such as setts, or the occurrence of discontinuities where the road hump meets the road surface.

3 Vehicles tested

The types of vehicles used in the study are listed in Table 2. They included bicycles, motor cycles, cars, buses, heavy goods vehicles and emergency service vehicles. Photographs of the vehicles used in the trial are shown in Appendix B, Plates 8 to 26.

The bicycles were owned and ridden by TRL staff. Laden and unladen bicycles were ridden over the hump profiles. Wet weather prevented the bicycle trials from being completed in one session. Thus the sample of riders and bicycles for the unladen trials was slightly different to that for the laden trials. Although the profile surfaces were damp during part of the unladen trials, tyre grip remained good throughout. The seven bicycles used in the unladen trials were: a mountain bike with microcellular polyurethane tyres, two hybrid mountain/road bikes, two standard town/touring bikes (one with dropped handlebars), a sports cycle with narrow tyres, and a folding bicycle (Brompton) with small wheels. The seven bicycles used in the laden trials (5 kg load in panniers, or on a carrier, or in a back pack) were: a hybrid mountain/road bike, five standard town/touring bikes, and a mountain bike with microcellular polyurethane tyres. Of the seven riders, five had taken part in the unladen trials.

The four motor cyclists were all experienced riders. One was a professional motor cycle courier. Another was a professional motor cycle instructor.

The public service vehicles were from a local bus service and were driven by their regular professional drivers. Of the three heavy goods vehicles taking part in the trials, one, the 17 tonne rigid dropside truck with a steel suspension, was TRL property. The other two were working commercial vehicles. The fire appliance and ambulances were accompanied by full crews and driven by professional drivers.

4 Method and measurements

4.1 Vehicle speeds

4.1.1 Range of vehicle speed tested and test order

The speed ranges selected for testing (10 to 40 mph for cars, 10 to 30 mph for the other vehicles) covered speeds likely to be found on the public roads. Ideally, all the motorised vehicles would have travelled over all the profiles at all the speeds selected for testing. However, the possibility of injuries to the vehicle occupants/riders and damage to the vehicles precluded driving some vehicles (eg buses, heavy goods vehicles and emergency vehicles) over some hump profiles at the higher speeds. Pre-trial tests with the cars had shown that passing over the profiles would be safe at speeds up to 40 mph in these vehicles. Cyclists rode over the humps at speeds in the speed range 10 to 20 mph.

Table 2 Vehicles used in the trials

Bicycles	Ten bicycles were used in the trials. Types of bicycles included: five standard town/touring bikes with and without dropped handlebars; a sports cycle with narrow tyres; two hybrid mountain/road bikes; a mountain bike with tyres filled with microcellular polyurethane; and a folding bicycle (Brompton) with small wheels.	(Plates 8 to 10)
Motor cycles	i Honda CG 125cc ii Honda NTV 650 cc iii Honda VFR 750 cc iv BMW R80 (800cc) and Squire QMI sidecar	(Plates 11 and 12)
Cars	i Ford Fiesta, 1300cc ii Ford Escort, 1600cc iii Ford Mondeo, 1800cc	(Plates 13 to 15)
Buses	i Optare City Pacer minibus 2000 series, steel suspension ii Optare Metro Rider midibus 600 series, air suspension iii Optare Low Rider single-deck bus, air suspension iv Optare Spectra double-deck bus (DAF), air suspension	(Plates 16 to 19)
Goods vehicles	i 17 tonne, Renault Dodge (Commando) rigid dropside, steel suspension ii 38 tonne, ERF EC10, 4x2 tractor, tri-axle trailer (tipper), steel suspension iii 38 tonne, Leyland Daf 95, 4x2 tractor, tri-axle trailer (tipper), air suspension	(Plates 20 and 21)
Emergency vehicles	i Dennis RS fire appliance ii GMC Chevrolet ambulance (Wheel Coach Conversion) iii Ford Transit ambulance (Devon Conversion) iv Iveco Turbo Daily 40-10 ambulance	(Plates 22 to 26)

In the trials, the cars were driven over the hump profiles at speeds of 10, 15, 20, 25, 30, 35 and 40 mph. To reduce the possibility of drivers and passengers anticipating the effects of regular increases in speeds on discomfort when travelling over the profiles, the speeds for the car tests were not increased incrementally and the order in which different hump profiles were tested was varied in the different speed levels. Table 3 shows the run order for the car tests. As a check on the consistency of discomfort reporting, the first speed level tested (20 mph) was repeated at the end of the test programme.

Table 3 Run order for car tests

Speed mph	*Profile test run order*				
20	P1	P4	P3	P5	P2
10	P5	P3	P2	P4	P1
30	P3	P5	P4	P2	P1
15	P2	P5	P1	P3	P4
40	P4	P1	P5	P2	P3
25	P4	P2	P3	P1	P5
35	P1	P4	P3	P5	P2
20	P1	P4	P3	P5	P2

As mentioned above, conducting pre-trial upper speed limits for the other types of vehicles was not practical. Therefore, for buses, heavy goods vehicles and emergency vehicles the profile crossing speeds were increased incrementally. This allowed drivers and passengers time to assess, based on the previous run, whether continuing with the next higher speed was safe and whether crossing the next profile should be carried out. As with cars, the order in which the profiles were tested was varied between the different speed levels. The upper limit for speeds tested for the different vehicle types are indicated in the relevant parts of Section 5.

The three cars made three passes over each profile. All the other vehicles, including bicycles, made only two passes.

4.1.2 Measurement of vehicle speed

The speed of all vehicles was recorded as they passed over the profiles using a calibrated Kustom Electronic Inc Type HR8 hand held radar gun. Before the trials, vehicle speedometers were calibrated against the radar system and drivers had practice runs at selected speeds.

Speeds for a sample of car, goods and public service vehicles were also recorded using a Correvit microwave recorder. The instrument uses a Doppler shift from a beam of microwaves pointed vertically towards the ground for recording purposes. Data from the Correvit, which was attached to the outside of the selected vehicle by a suction cup, were fed into a solid state data logger positioned within the vehicle being driven. Correvit speed information and vertical acceleration measurements (see Section 4.2.3), recorded simultaneously, were stored in the data logger for down loading later to a portable computer.

4.2 Assessment of driver/passenger/rider discomfort

For most of the vehicle types (cars, buses, goods vehicles and emergency service vehicles), two measures were used to evaluate the discomfort experienced by vehicle occupants:

i a subjective assessment of discomfort on a 0 to 6 scale made by one or more vehicle occupants;

ii a record of the peak upward vertical acceleration experienced by one vehicle occupant at a particular location in the vehicle.

In previous studies these two measures have shown generally good correlation with each other (Watts, 1973).

For bicycles and motor cycles, the discomfort ratings of the riders were recorded. For cars and public service vehicles, the discomfort ratings of the passengers were recorded. For the goods vehicles, discomfort ratings of the driver were recorded. For the fire appliance, discomfort ratings of the crew were recorded. For the ambulances, discomfort ratings of passengers lying or sitting in the rear were recorded.

4.2.1 Subject participation

Members of the public were recruited to act as passengers in the cars, buses and ambulances. Their ages ranged from 18 to 55 years old.

In the three cars tested, six members of the public were driven over the profiles as passengers in the front and rear seats. Each car was driven over the test profiles three times (each time with a different set of two passengers). For consistency, the passengers remained in the same seat position (front or rear) throughout the trial.

In the four buses tested, 12 members of the public acted as bus passengers and were allocated seats in the front, middle and back areas (nearside and offside) of the bus. For the double-deck bus, the passengers were divided into two groups and allocated seats on the upper and lower decks, in a similar manner to the single deck buses. As for the car trials, passengers in buses retained their allocated seating positions throughout the series of trial runs.

4.2.2 Recording passenger discomfort

The discomfort rating scale used to assess passenger and driver discomfort was the same as that previously used by Watts (1973) and Hodge (1993). The aim of the discomfort measurements was to establish the level of discomfort experienced by occupants in the vehicles passing over the profiles at predetermined speeds. The scale used is shown below:

0 - Comfortable
1 -
2 - Slightly uncomfortable
3 -
4 - Uncomfortable
5 -
6 - Very uncomfortable.

On completion of each speed level over a selected profile and after completing their discomfort rating scale, passengers' drivers' and riders' opinions about the profile and their experiences of crossing the profile were recorded.

The values of discomfort rating were primarily used to rank the different profiles that were being assessed during the trials. The assessment of discomfort rating for a particular hump at a particular speed varies between subjects and whilst the average value will give an indication of the average level of discomfort likely to be experienced by the general public, a similar trial with a different group of subjects may produce results that are slightly lower or higher than those shown. Thus, as in this trial, when carrying out tests on novel profiles it is advisable to carry out comparison tests on a 'standard' 75mm high round-top or flat-top hump profile.

4.2.3 Measurement of vertical acceleration

Passenger discomfort is influenced by the vertical acceleration a driver or passenger experiences as the vehicle crosses over a hump or cushion. For a given speed, the greater the vertical acceleration, the greater the discomfort (Watts, 1973). In Danish trials, Kjemtrup found occupants of vehicles unwilling to accept a maximum peak vertical acceleration of greater than about 0.7g (where g is the force of gravity and equals 9.8 m/s^2). Kjemtrup also noted that for effective speed reduction, humps should cause peak accelerations higher than 0.5g (Kjemtrup, 1990).

The peak upward acceleration experienced by the vehicle occupants passing over the hump profiles was measured using an accelerometer with a range of $\pm$ 2g, connected to a solid state data logger. Generally, the accelerometer, held in a metal plate, was strapped either to the lap of a driver or a passenger, depending on the vehicle being tested. Thus, the vertical acceleration experienced was that of a vehicle occupant and not that of the vehicle. A circular spirit level built into the metal plate helped the measurement team to maintain the instrument in a horizontal plane.

Cars. In the three cars, measurements were made with the accelerometer strapped to the lap of the front seat passenger. Also in the car were the driver, a rear seat passenger and the data logger operator.

Buses. In the buses, measurements were made with the accelerometer strapped to the lap of a passenger sitting over the rear axle of the bus. On the double-deck bus the passenger was on the lower deck.

Fire appliance. In the fire appliance, measurements were made with the accelerometer strapped to the lap of one of the fire crew.

Measurements of vertical acceleration were not made for the pedal cyclists, motor cyclists or commercial vehicle drivers.

5 Results

5.1 Bicycles

5.1.1 Unladen cyclists

Table 4 shows the average discomfort ratings for each unladen cyclist at the approximate crossing speeds of 10 and 20 mph when crossing each of the different hump profiles. The values of discomfort recorded by the different cyclists when crossing the same hump profile at the same speed varied considerably. This is not surprising since the discomfort experienced will be a combination of the 'sensitivity' of the cyclist and the type of bicycle being ridden.

Profile P3, *the 5m long round-top hump*, was ranked as more comfortable than P2, *the 3.7m long round-top hump* by 6 of the 7 cyclists, the other cyclist giving them equal ranking.

Table 4 Discomfort rating for the different hump profiles — unladen cyclists

	Average discomfort rating (defined in section 4.2.2)									
	P1 Sinusoidal 3.7m long		*P2 Round-top 3.7m long*		*P3 Round-top 5.0m long*		*P4 Flat-top sinusoidal ramp*		*P5 Flat-top straight ramp*	
	Speed (mph)		*Speed (mph)*		*Speed (mph)*		*Speed (mph)*		*Speed (mph)*	
Cyclist and type of bicycle	*10*	*20*	*10*	*20*	*10*	*20*	*10*	*20*	*10*	*20*
1 Mountain bike, polyurethane tyres	0.5	1.0	0.5	2.5	0.0	1.0	1.0	3.5	1.5	3.5
2 Hybrid mountain/road bike (i)	3.5	5.5	3.0	5.0	1.5	2.0	4.0	5.0	3.0	6.0
3 Hybrid mountain/road bike (ii)	1.0	—	2.0	—	1.0	—	2.0	—	2.0	—
4 Standard tourer (i)	1.5	3.0	3.0	3.5	1.5	2.0	4.0	5.0	3.0	4.0
5 Sports bike	0.0	1.5	2.0	2.0	1.0	2.0	2.0	3.5	3.0	3.0
6 Standard tourer (ii)	0.0	1.0	0.0	1.0	0.0	1.0	1.0	3.0	1.0	1.5
7 Folding bicycle with small wheels	1.5	4.0	2.0	4.5	1.0	1.5	2.5	4.5	3.0	5.0
Overall average rating	1.1	2.7	1.8	3.1	0.9	1.6	2.4	4.1	2.4	3.8

Profile P1, *the 3.7m long sinusoidal hump*, was ranked as more comfortable than P2, *the 3.7m long round-top hump*, by 5 of the 7 cyclists, 1 cyclist ranked P1 as more uncomfortable than P2 and the other cyclist gave them equal ranking.

Profiles P4, *the flat-top hump with sinusoidal ramps*, and P5, *the flat-top hump with straight ramps*, were ranked as more uncomfortable than P2, *the 3.7m long round-top hump*, by 6 of the 7 cyclists, the other cyclist giving them equal ranking. Cyclists were not consistent in the relative ranking of profiles P4 and P5. Three of the seven cyclists ranked P4 more comfortable than P5, two cyclists gave them equivalent ranking, and two ranked P4 as more uncomfortable than P5.

The overall discomfort rating (averaged for all cyclists) for each hump profile at speeds of 10 mph and 20 mph is given in Table 4. The relationship between the overall discomfort rating and speed over the humps is shown in Figure 3. For all the hump profiles, the overall average discomfort ratings increased as speed increased from 10 to 20 mph and were within the range 0 (comfortable) to 4 (uncomfortable).

The overall discomfort ratings at 15 mph (average of ratings at 10 and 20 mph) are given in Table 5 and shown as a bar chart in Figure 4. The most uncomfortable hump profiles to ride over were P4, the flat-top hump w*ith sinusoidal ramps*, and P5, *the flat-top hump with the straight ramps*. There was little difference between the overall discomfort ratings for these hump profiles with a value of about 3.2 at 15 mph. The most comfortable hump profile for the cyclists to ride over was P3, *the 5m long round-top hump*, with an overall discomfort rating of about 1.2 at 15 mph. Profile P1, *the 3.7 m long sinusoidal hump*, was more comfortable than P2, *the 3.7m long round-top hump*, with overall discomfort ratings at 15 mph of about 1.9 and 2.4 respectively.

Table 5 Cyclists — average discomfort ratings

	Average discomfort rating (defined in section 4.2.2)			
Hump profile	*Unladen 10 mph*	*Unladen 20 mph*	*Unladen 15 mph**	*Laden 15 mph*
P1 3.7m long, sinusoidal	1.1	2.7	1.9	1.3
P2 3.7m long, round-top	1.8	3.1	2.4	2.1
P3 5.0m long, round-top	0.9	1.6	1.2	0.9
P4 Flat-top, sinusoidal ramps	2.4	4.1	3.2	3.8
P5 Flat-top, straight ramps	2.4	3.8	3.1	3.0

** Results for 15 mph are the average of 10 and 20 mph*

5.1.2 Laden cyclists

The overall discomfort ratings averaged for all the laden cyclists (5kg load) crossing the hump profiles at 15 mph are given in Table 5 and Figure 4. The overall discomfort ratings of the laden cyclists were similar to those of the unladen cyclists but, because not all riders and bicycles were common to both unladen and laden data sets, no general statement can be made about whether the hump profiles were more or less uncomfortable to cross when laden compared to when unladen.

The ranking order of the different hump profiles in terms of overall average discomfort was the same for the laden and unladen cyclists.

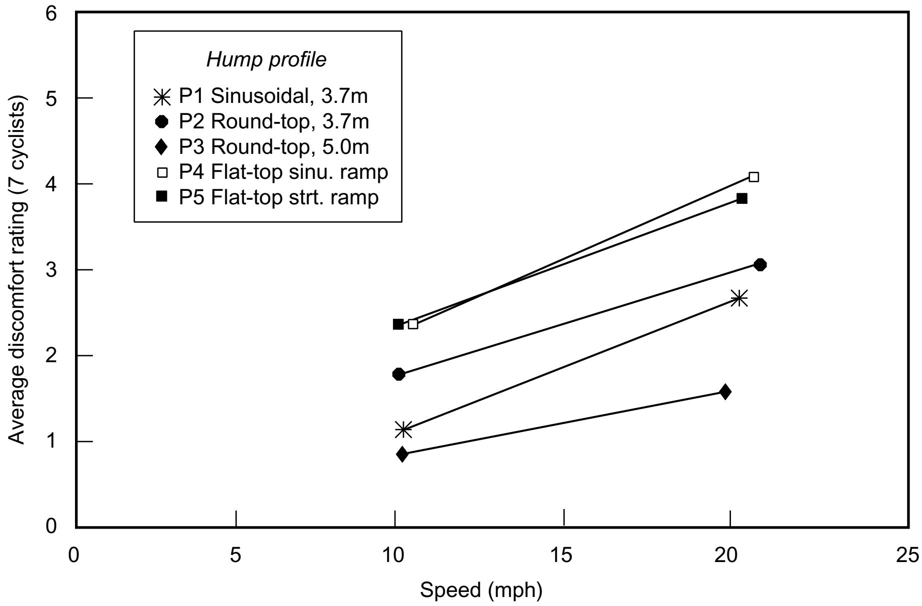


Figure 3 Unladen cyclists

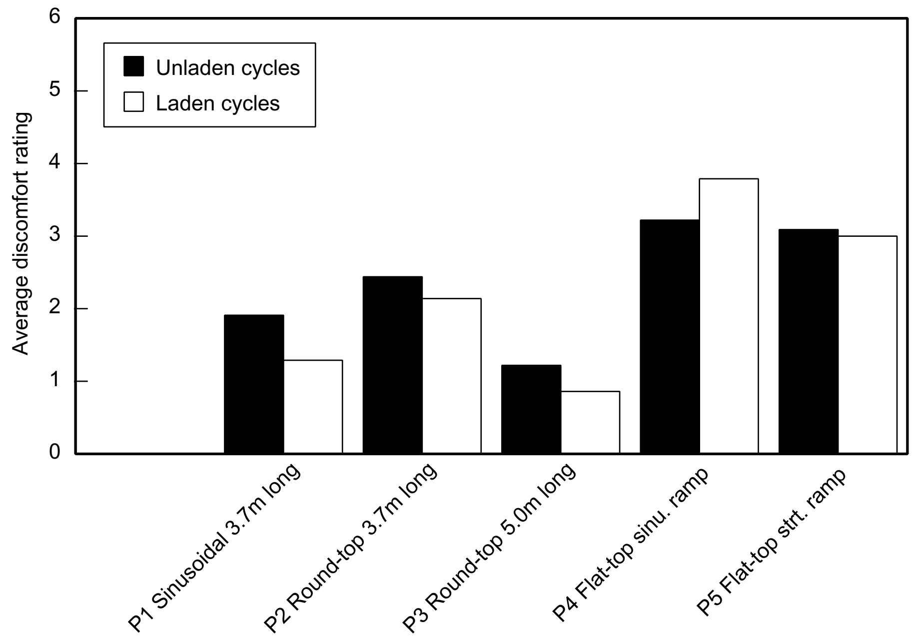


Figure 4 Unladen and laden cyclists (at 15 mph)

5.1.3 Discussion of results for cyclists

The overall average discomfort ratings for the unladen and laden cyclists shown in Table 5 and Figure 4 indicate that there would be some advantage in terms of reducing the discomfort experienced by cyclists in selecting a sinusoidal or round-top profile when installing humps.

Profile P3, *the 5m long round-top hump*, gave the least discomfort to cyclists but this profile also gave the least discomfort to car occupants and its use would be likely to result in higher car speeds than profile P2, *the 3.7m long round-top hump* (see Section 5.3).

Profile P1, *the 3.7 m long sinusoidal hump*, gave less discomfort to cyclists than profile P2, *the 3.7m long round-top hump.* However, the difference in discomfort was not large. Depending on the method of hump construction used in hump schemes on the public roads, there may be extra difficulty/expense in constructing the sinusoidal profile rather than a round-top profile and this would need to be taken into account when deciding which hump profile was appropriate.

Some cyclists taking part in the tests said that, while there were differences in discomfort between the different hump profiles tested, it was noticeable that the test humps had been constructed so there was no upstand or discontinuity where humps met the road surface. Such upstands are often present at humps on the public road and are likely to increase the discomfort experienced by cyclists. It may be more important for the local authority to ensure that humps have no upstand or discontinuity than whether humps have a round-top or sinusoidal profile.

The profiles P4 and P5, *the 8m flat-top hump with sinusoidal ramps and the 8m flat-top hump with straight ramps (gradient 1:13),* gave the most discomfort for cyclists. Some cyclists commented adversely on the double jolt felt at the flat-top humps. Some were also concerned about discomfort and a potential loss of control when reaching the bottom of the off ramps, particularly when crossing at about 20 mph. In order to reduce discomfort to cyclists, the use of these hump profiles should be avoided on routes used by substantial numbers of cyclists except at humped pedestrian crossings where a flat surface is required.

Other traffic calming measures such as speed cushions (vertical deflections which do not span the whole carriageway) and chicanes (horizontal deflections) do not generally cause cyclists discomfort. Like most traffic calming measures, including road humps, these measures have some operational problems and are not appropriate in all situations (DETR, 1997 and 1998). However, their use should be considered when selecting traffic calming measures, particularly on routes used by substantial numbers of cyclists. It should be noted that cycle bypass lanes are recommended at chicane sites and other road narrowings because of concerns about conflicts between cyclists and overtaking traffic (DOT, 1997).

5.2 Motor cycles and motor cycle/sidecar combination

Section 5.2.1 gives the results from trials of the three motor cycles and Section 5.2.2 the results from the trials of the motor cycle and side-car combination.

5.2.1 Motor cycles

The average discomfort ratings for the riders of the three motor cycles (125cc Honda CG, 650cc Honda NTV and 750cc Honda VFR) when crossing the hump profiles are given in Table 6 and Figure 5a. The discomfort ratings for the different profiles varied but all showed an increase with speed from about 0.1 to 1.0 at 10 mph to 2.0 to 3.5 at 25 mph. At 10 mph, the discomfort for motorcycle riders crossing the hump profiles was similar to that for car occupants (see Section 5.3). However, the discomfort for motor cycle riders increased more rapidly with speed than for car occupants. There were no handling problems reported by any of the motorcyclists when crossing the hump profiles at the speeds tested.

At 10 mph, the average discomfort ratings for the three motorcyclists crossing the round-top and sinusoidal profiles, P1, P2 and P3 were similar at a level just above the 0 (comfortable) rating. At higher speeds (15 to 25 mph), the discomfort rating for profile P3, *the 5m long round-top hump*, was less than that of P1, *the 3.7m long sinusoidal hump*, and P2, *the 3.7 m long round-top hump*. The average discomfort ratings for profile P1, *the 3.7m long sinusoidal hump*, were similar to those of profile P2, *the 3.7 m long round-top hump,* throughout the speed range.

At 10 mph, the average discomfort rating of the flat-top hump profiles P4 and P5 were similar to each other at about 1.0 and were higher than those of the round-top and sinusoidal humps P1, P2 and P3. As the speed increased, the difference between the ratings for 3.7 m long round-top and sinusoidal humps (P1 and P2) and those of flat-top humps (P4 and P5) became smaller. The average discomfort ratings for profile P4, *the flat-top hump with sinusoidal ramps,* were similar to those of profile P5, *the flat-top hump with straight ramps,* throughout the speed range.

In summary, it would seem that there would be little, if any, benefit in terms of reduced discomfort to motorcyclists in using profile P1, *the 3.7m long sinusoidal hump* rather than profile P2, *the 3.7m long round-top hump*. There would also be little benefit, if any, in using profile P4, *the flat-top hump with sinusoidal ramps,* rather than profile P5, *the flat-top hump with straight ramps.*

Profile P2, *the 3.7m long round-top hump* had slightly lower discomfort ratings for motorcyclists than P5, *the flat-top hump with straight ramps*.

The use of profile P3, *the 5m long round-top hump,* would reduce discomfort to motorcyclists in the speed range 15 to 25 mph but might encourage higher speeds as a consequence.

5.2.2 Motor cycle and side-car combination

The average discomfort ratings for the rider and sidecar passenger of the motor cycle (BMW R80) and sidecar

Table 6 Motor cyclists - average speed and discomfort rating

	Average speed and discomfort rating (DR)*									
	P1 Sinusoidal 3.7m long		*P2 Round-top 3.7m long*		*P3 Round-top 5.0m long*		*P4 Flat-top sinusoidal ramp*		*P5 Flat-top straight ramp*	
Speed level	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*
10 mph	10.5	0.3	10.0	0.3	10.1	0.1	10.3	1.0	10.5	1.0
15 mph	14.0	1.3	14.3	1.3	13.8	0.6	14.0	2.0	13.7	1.5
20 mph	19.6	2.5	20.0	2.2	19.2	1.3	19.3	2.7	19.7	2.3
25 mph	23.8	2.8	23.6	2.7	23.5	2.0	24.8	3.0	23.5	3.5
Overall average	17.0	1.7	17.0	1.6	16.7	1.0	17.1	2.2	16.9	2.1

** Combined results from riders of three motor cycles; DR is defined in section 4.2.2*

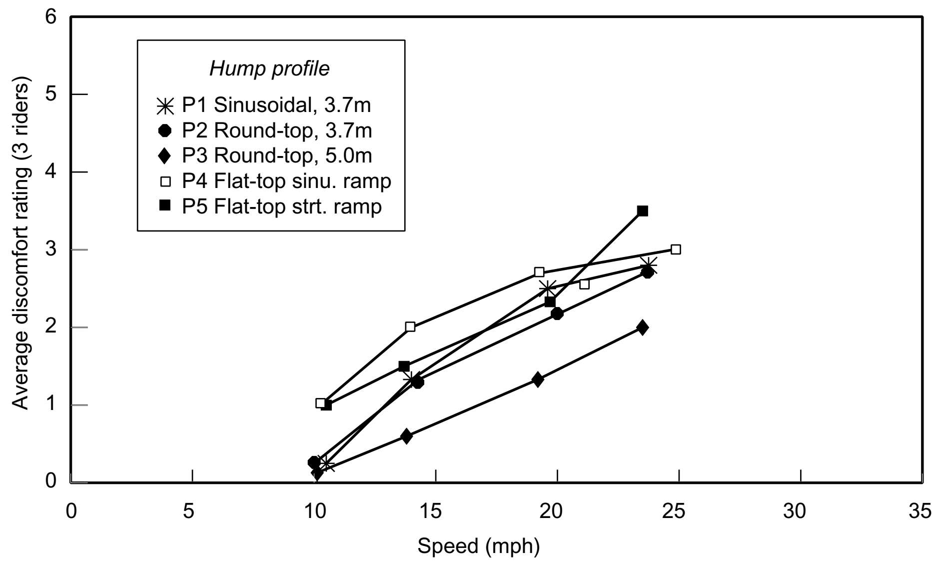


Figure 5a Motorcycles — combined results from small, medium and large motor cycles

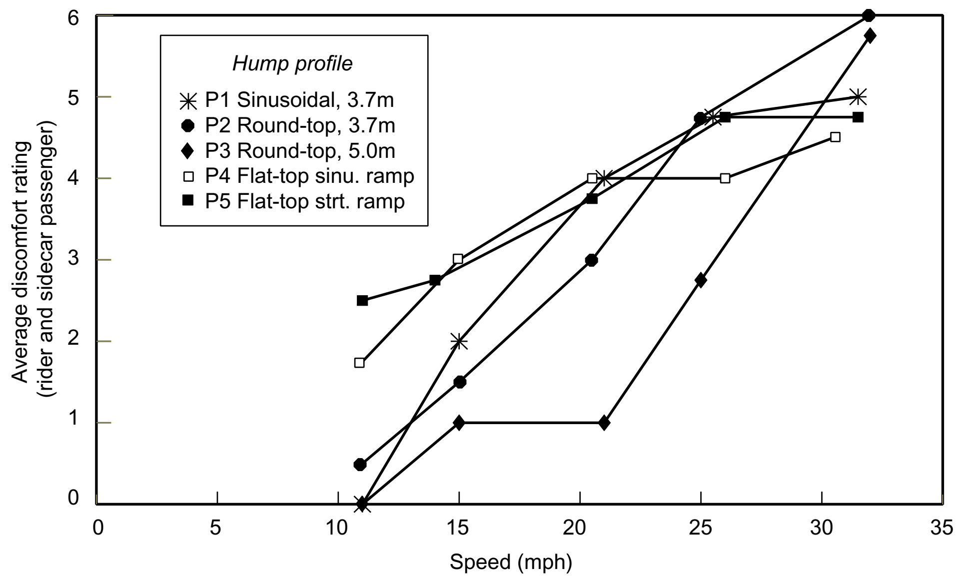


Figure 5b Motor cycle and sidecar combination

(Squire QMI) combination when crossing the hump profiles are given in Table 7 and Figure 5b. There were no handling problems reported by the rider of the motor cycle and side-car combination when crossing the hump profiles at the speeds tested.

For a given speed and hump profile, the combined discomfort rating for the rider and passenger in the motor cycle and sidecar combination (Figure 5b) was generally higher than that for the combined results for riders of motor cycles without sidecars (Figure 5a). However, the pattern of results in Figure 5b was similar to that in Figure 5a with all profiles showing an increase in discomfort rating with increasing speed.

As with the riders of motor cycles without sidecars, it would seem that there would be little, if any, benefit in terms of reduced discomfort to motorcycle and sidecar riders and passengers in using profile P1, *the 3.7m long sinusoidal hump* rather than profile P2, *the 3.7m long round-top hump*. There would also be little benefit, if any, in using profile P4, *the flat-top hump with sinusoidal ramps,* rather than profile P5, *the flat-top hump with straight ramps*.

At the lower speeds, 10 to 15 mph, profile P2, *the 3.7m long round-top hump* had lower discomfort ratings than P5, *the flat-top hump with straight ramps*. However, the benefit in terms of reduced discomfort in using profile P2 rather than profile P5 was less apparent at the higher speeds and at 30 mph, profile P5 gave less discomfort than profile P2.

The use of profile P3, *the 5m long round-top hump* rather than profile P2, *the 3.7m long round-top hump,* would reduce discomfort to riders and passengers of motor cycle and sidecar combinations but might encourage higher speeds as a consequence.

Table 7 Motor cycle and sidecar combination — average speed and discomfort rating

	Average speed and discomfort rating (DR)*									
	P1 Sinusoidal 3.7m long		*P2 Round-top 3.7m long*		*P3 Round-top 5.0m long*		*P4 Flat-top sinusoidal ramp*		*P5 Flat-top straight ramp*	
Speed level	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*
10 mph	11.0	0.0	11.0	0.5	11.0	0.0	11.0	1.8	11.0	2.5
15 mph	15.0	2.0	15.0	1.5	15.0	1.0	15.0	3.0	14.0	2.8
20 mph	21.0	4.0	20.5	3.0	21.0	1.0	20.5	4.0	20.5	3.8
25 mph	25.5	4.8	25.0	4.8	25.0	2.8	26.0	4.0	26.0	4.8
30 mph	31.5	5.0	32.0	6.0	32.0	5.8	30.5	4.5	31.5	4.8
Overall average	20.8	3.2	20.7	3.2	20.8	2.1	20.6	3.5	20.6	3.7

** Combined results from rider and sidecar passenger; DR is defined in section 4.2.2*

5.3 Cars

The average values of peak vertical acceleration (VA) and discomfort rating (DR) for passengers in a small, a medium and a large car (Ford Fiesta, Ford Escort and Ford Mondeo) when traversing the hump profiles are shown in Appendix C. The results for the three sizes of car were very similar and therefore have been combined here. Overall average values for all three cars are given in Table 8 and Figures 6, 7a and 7b. Measurements of discomfort rating and vertical acceleration were carried out at speeds from 10 mph to 40 mph. There were no handling problems reported by the car drivers when crossing the hump profiles.

As previously mentioned, previous studies have shown that, in cars, the average discomfort rating of a group of subjects correlates well with the positive peak vertical acceleration experienced by the subjects as the vehicle passes over a road hump. Watts (1973), found that a sample of four subjects in passenger cars were prepared to suffer, on average, a subjective discomfort rating of up to 1.7 (on the same scale as used here) when crossing a hump. This was just below the ‘slightly uncomfortable’ discomfort rating of 2. A 1.7 discomfort rating was found to be equivalent to a peak acceleration of about 0.4g.

For effective speed reduction, the passenger discomfort and peak vertical acceleration experienced at a hump should be low at low speeds and increase with increasing vehicle speeds to levels that are likely to be uncomfortable. In Danish trials (Kjemtrup, 1990) it was the impression of trial participants that a peak vertical acceleration value greater than 0.7g was unacceptable. This was equivalent to a discomfort rating of about 3, between ‘slightly uncomfortable’ and ‘uncomfortable’. Kjemtrup noted that for effective speed reduction the humps should be capable of producing peak accelerations higher than 0.5g at higher speeds.

Figure 6 shows, for the current hump trials, the relationship obtained between the average peak vertical acceleration of the front seat passenger and the average discomfort rating for three front and three rear car passengers. The correlation coefficient for the trend line shown was 0.96. In Figure 6, a peak vertical acceleration of 0.7g corresponds to an average discomfort rating for six passengers tested of about 2.6.

Figures 7a and 7b show the relationships between average discomfort rating and peak vertical acceleration

Table 8 Cars*— average speed, passenger discomfort rating and peak vertical acceleration

	Average speed, discomfort rating (DR) and peak vertical acceleration (VA)														
	P1 Sinusoidal 3.7m long			*P2 Round-top 3.7m long*			*P3 Round-top 5.0m long*			*P4 Flat-top sinusoidal ramp*			*P5 Flat-top straight ramp*		
Speed level	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*
10 mph	10.2	0.4	0.23	10.6	0.6	0.20	10.9	0.1	0.13	10.6	0.8	0.28	10.0	0.8	0.27
15 mph	15.0	0.8	0.24	15.4	1.1	0.23	15.0	0.3	0.17	15.5	1.2	0.32	15.3	1.3	0.35
20 mph	20.1	1.3	0.35	20.3	1.5	0.40	20.5	0.8	0.25	20.8	1.8	0.46	20.6	1.6	0.45
25 mph	25.0	1.9	0.41	25.3	2.0	0.40	25.7	1.3	0.33	25.5	2.4	0.61	24.7	2.3	0.63
30 mph	30.3	2.1	0.46	29.8	2.3	0.46	30.2	1.6	0.43	30.0	3.1	0.80	30.1	2.7	0.86
35 mph	35.0	2.1	0.51	34.8	2.5	0.54	35.0	2.0	0.49	35.2	3.6	0.87	34.9	3.8	0.95
40 mph	40.0	2.2	0.61	40.0	2.6	0.64	40.4	2.3	0.61	40.6	3.4	0.87	40.2	3.8	1.04
OveralL average	25.1	1.6	0.40	25.2	1.8	0.41	25.4	1.2	0.34	25.5	2.3	0.60	25.1	2.3	0.65

** Combined data from all three cars; DR is defined in section 4.2.2*

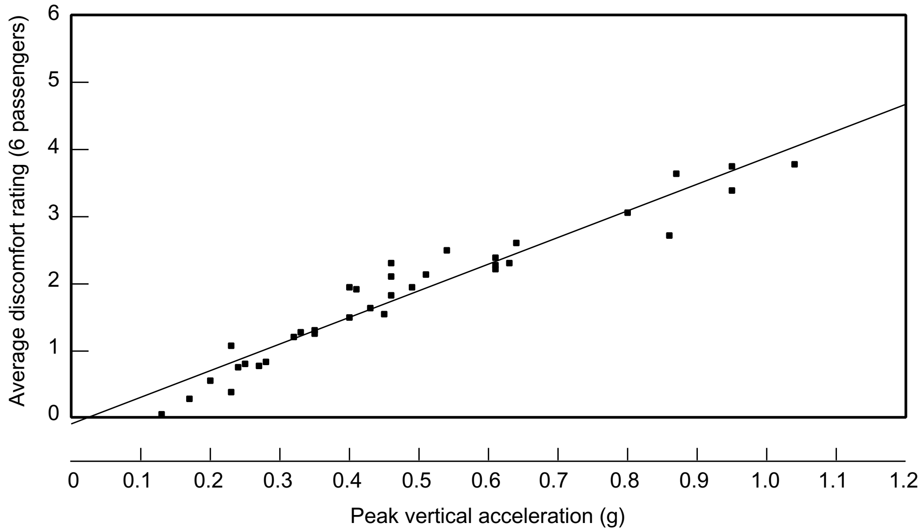


Figure 6 Cars — correlation between peak vertical acceleration and average discomfort rating

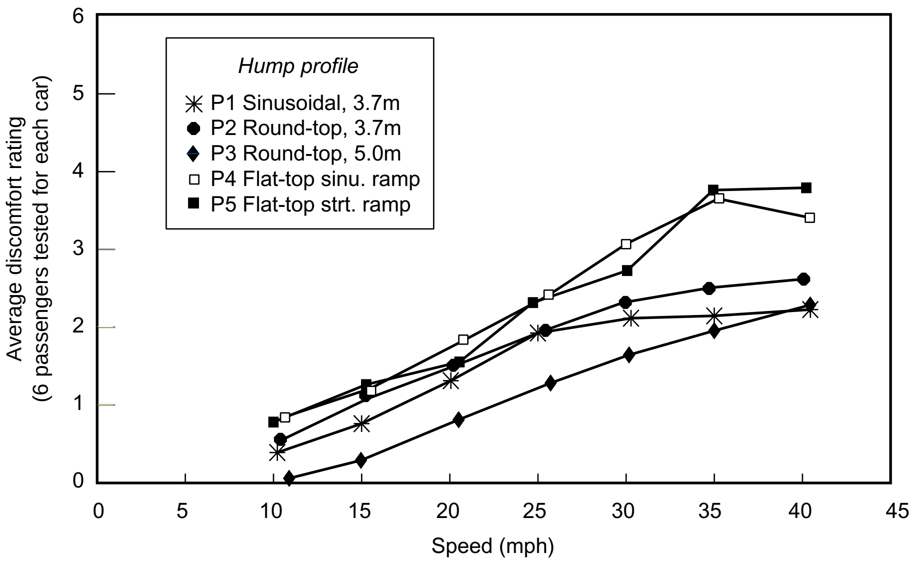


Figure 7a Cars — combined results from the small, medium and large cars

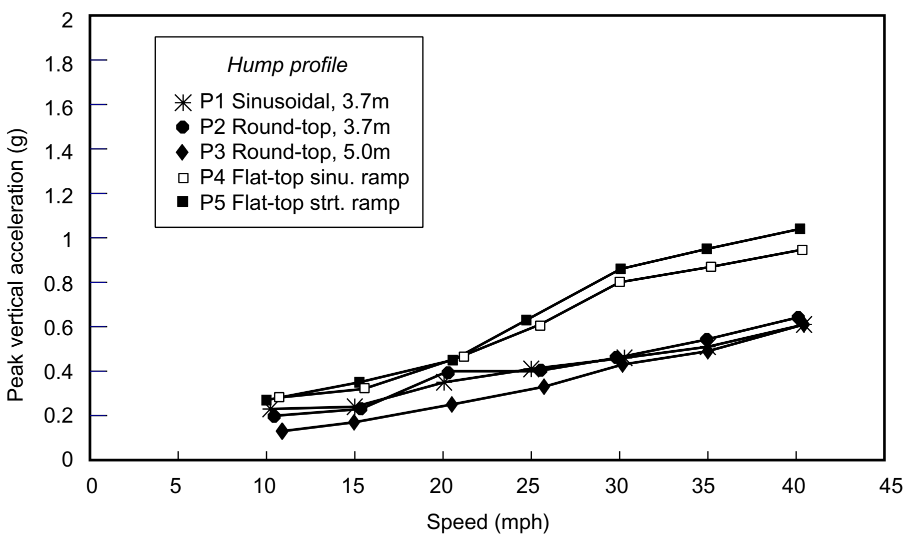


Figure 7b Cars — combined results from small, medium and large cars (accelerometer on lap of front seat passenger)

and vehicle speed. For all five hump profiles, increased speed caused increases in peak vertical acceleration and passenger discomfort.

For both discomfort rating and peak vertical acceleration, there was little difference in the values measured when crossing profile P4, *the flat-top hump with sinusoidal ramps*, and profile P5, *the flat-top hump with straight ramps*. The overall average values across all speed levels for discomfort rating and peak vertical acceleration respectively were 2.3 and 0.60g for profile P4, and 2.3 and 0.65g for profile P5.

The values of discomfort rating for profile P2, *the 3.7m long round-top hump*, were slightly higher than those for profile P1, *the 3.7m long sinusoidal hump* except at the 25 mph speed level. However, there was little difference between the peak vertical acceleration values measured for profiles P2 and P1. The overall average values across all speed levels for discomfort rating and peak vertical acceleration respectively were 1.8 and 0.41g for profile P2, and 1.6 and 0.40g for profile P1.

Values of both discomfort rating and peak vertical acceleration, were higher for the 8m long flat-top hump profiles P4 and P5 than for the 3.7m long round-top and sinusoidal profiles P2 and P1. This was particularly noticeable for speeds greater than 20 mph.

The values of discomfort rating measured when crossing profile P3, *the 5m long round-top hump*, were lower than those for profile P2, *the 3.7m long round top hump*. The overall average value across all speed levels for discomfort rating was 1.2 for profile P3, and 1.8 for profile P2. The values of peak vertical acceleration for profile P3 were also lower than those for profile P2 at speeds below 30 mph. At the higher speeds (30 to 40 mph), the values of peak vertical acceleration for profile P3 were similar to those for profile P2. The overall average values across all speed levels for peak vertical acceleration were 0.34g for profile P3 and 0.41g for profile P2.

Studies of 75mm high round-top and flat-top humps on the public roads indicate that the mean speeds of cars crossing 3.7m long round-top humps are about 12 to 18 mph and the mean speeds of cars crossing flat-top humps with ramp gradients of 1:10 to 1:15 are about 10 to 15 mph. (Webster and Layfield, 1996).

The results shown in Figure 7a are in line with these findings. In the speed range 10 to 20 mph, the discomfort ratings of profile P2, *the 3.7m long round-top hump*, are slightly lower than for profile P5, *the flat-top hump with straight ramps.* On the public roads, car drivers are likely to reduce speeds to reduce the discomfort to an acceptable level when crossing humps so it is likely that crossing speeds on the public roads would be slightly slower at profile P5 than profile P2.

Figure 7a shows that above 20 mph the discomfort rating for profile P5, *the flat-top hump with straight ramps*, increases more rapidly with speed than that for profile P2, *the 3.7m long-round top hump*. Thus profile P5 might be more suitable than profile P2 at discouraging car drivers who might otherwise drive at these higher speeds.

The use of profile P3, *the 5m long round-top hump*, rather than profiles P2 or P5 would reduce discomfort for car drivers travelling at similar speeds. However it is possible that drivers on the public roads would increase speed to bring the discomfort experienced at profile P3 in line with that experienced at profiles P2 and P5 and thus the mean crossing speed for cars at profile P3 is more likely to be about 20 to 25 mph.

5.4 Buses

5.4.1 Minibus (Optare City Pacer)

The average values of speed and discomfort rating for 12 passengers sitting in the Optare City Pacer minibus are given in Table 9 and Figure 8. Measurements of discomfort rating and vertical acceleration were carried out at speeds from 10 mph to 25 mph.

The driver reported no handling problems. He found the vehicle a bit bouncy crossing the hump profiles at 10 mph and the handling better at 25 mph than 20 mph. Additional runs were carried out at 10 mph and 15 mph with some passengers standing. At 10 mph, the standing passengers reported that it was more comfortable than sitting. At 15 mph, the subjects reported that the discomfort was about the same, standing or sitting.

Table 9 and Figure 8 show that the discomfort ratings for passengers sitting in the minibus increased with speed from about 0.5 to 2 at 10 mph to 3.5 to 5 at 20 to 25 mph.

Table 9 Minibus (Optare City Pacer) — average speed and discomfort rating

	Average speed and discomfort rating (DR)*									
	P1 Sinusoidal 3.7m long		*P2 Round-top 3.7m long*		*P3 Round-top 5.0m long*		*P4 Flat-top sinusoidal ramp*		*P5 Flat-top straight ramp*	
Speed level	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*	*Speed (mph)*	*DR*
10 mph	10.5	0.7	10.7	0.9	10.7	0.3	10.5	2.0	10.5	2.1
15 mph	14.8	3.6	14.5	2.6	15.0	1.0	15.0	3.6	14.5	3.6
20 mph	19.5	5.0	20.5	5.2	20.5	3.4	20.0	4.7	20.5	4.2
25 mph	27.0	4.8	25.5	5.2	26.5	4.7	26.0	3.9	27.0	3.6
Overall average	18.0	3.5	17.8	3.5	18.2	2.3	17.9	3.5	18.1	3.4

** Combined results from 12 passengers; DR is defined in section 4.2.2*

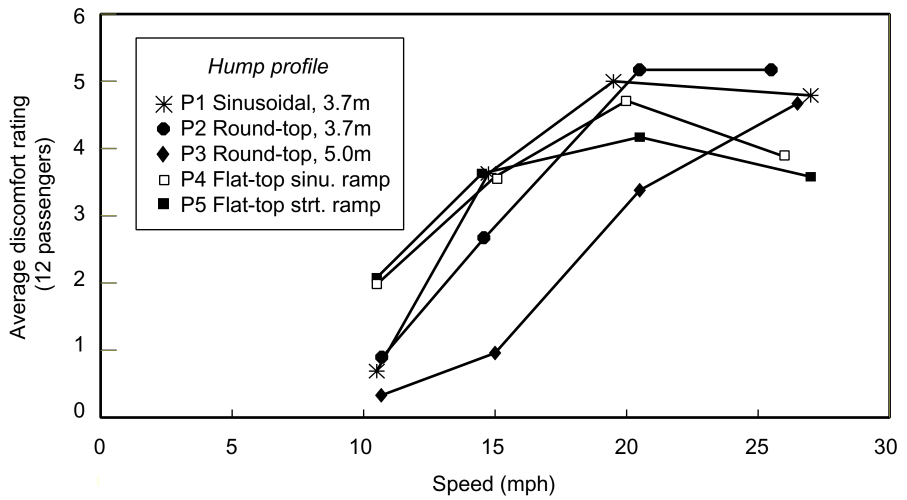


Figure 8 Minibus (Optare City Pacer) (all passengers sitting)

The average discomfort ratings for profile P2, *the 3.7m long round-top hump*, and profile P1, *the 3.7m long sinusoidal hump* started fairly low at just under 1 point at 10 mph, increased rapidly to about 5 at 20 mph, and remained at about this level at 25 mph. There was generally little difference in discomfort rating between these two profiles.

The average discomfort rating for profile P3, *the 5m long round-top hump*, also started low (about 0.5) at 10 mph and then increased steadily to about 4.5 at 25 mph. The average discomfort rating for profile P3 was substantially lower than all the other profiles at 15 mph and to a lesser extent at 20 mph.

At 10 mph, the average discomfort ratings for profile P4, *the flat-top hump with sinusoidal ramps*, and profile P5, *the flat-top hump with straight ramps* were about 2 and were higher than the other profiles. The average discomfort ratings for profiles P4 and P5 increased to about 4 to 4.5 at 20 mph and then remained just below this level at 25 mph. Again, there was generally little difference in discomfort rating between these two profiles.

In summary, it would seem that the rating of discomfort by minibus passengers was quite sensitive to changes in vehicle speed over the hump profiles, particularly in the speed range 10 to 20 mph. At low speeds (about 10 mph) the round-top and sinusoidal profiles P1, P2 and P3 provided less discomfort to passengers in the minibus than the flat-top profiles P4 and P5. However, as speeds increased, the benefit in terms of passenger discomfort provided by profiles P1 and P2 was rapidly reduced such that profiles P4 and P5 provided less discomfort at speeds of 20 to 25 mph.

The lowest discomfort ratings were given by profile P3, the longer round-top hump, at speeds of 10 to 20 mph and by profiles P4 and P5, the flat-top humps, at 25 mph. It should be noted that, at speeds of 20 to 25 mph, the values of discomfort rating for all the profiles were relatively high (in the uncomfortable region of the scale) and that such speeds would be deemed unsuitable by bus operators and passengers.

There would be little, if any, benefit in terms of reduced discomfort to minibus passengers in using profile P1, *the 3.7m long sinusoidal hump* rather than profile P2, *the 3.7m long round-top hump*. There would also be little benefit, if any, in using profile P4, *the flat-top hump with sinusoidal ramps*, rather than profile P5, *the flat-top hump with straight ramps*.

5.4.2 Midibus (Optare Metro Rider)

The average values of speed, discomfort rating (12 sitting passengers) and vertical acceleration for the Optare Metro Rider midibus are given in Table 10 and Figures 9a and 9b. Measurements of discomfort rating and vertical acceleration were carried out at speeds from 10 mph to 25 mph. The driver reported some handling problems. Profile P5 was found to be ‘tricky’ at 10 mph, the bus grounded momentarily on profile P2 at 15 mph and profile P4 at 20 mph, and the bus was difficult to handle on profiles P1 and P2 at 20 mph and 25 mph.

Additional runs were carried out at 10 mph, 15 mph and 20 mph with some passengers standing. At 10 mph, the standing passengers reported that it was more comfortable than sitting, but difficult to balance. At 15 mph and 20 mph, the subjects reported that the discomfort was about the same, standing or sitting.

The values of discomfort rating recorded for passengers sitting in the midibus were similar to those in the minibus. The discomfort ratings increased with speed from about 0.5 to 2 at 10 mph to 3.5 to 5 at 20 to 25 mph.

The average discomfort ratings for profile P2, *the 3.7m long round-top hump*, and profile P1, *the 3.7m long sinusoidal hump* started fairly low at about 1 at 10 mph, increased rapidly to about 5 at 20 mph, and remained at about this level at 25 mph. There was generally little difference in discomfort rating between these two profiles.

The average discomfort rating for profile P3, *the 5m long round-top hump*, also started low (about 0.5) at 10 mph and then increased steadily to about 4.5 at 25 mph. The average discomfort rating for profile P3 was substantially lower than all the other profiles at 15 mph.

Table 10 Midibus (Optare Metro Rider) — average speed, passenger discomfort rating and peak vertical acceleration

	Average speed, discomfort rating[1] (DR) and peak vertical acceleration[2] (VA)														
	P1 Sinusoidal 3.7m long			*P2 Round-top 3.7m long*			*P3 Round-top 5.0m long*			*P4 Flat-top sinusoidal ramp*			*P5 Flat-top straight ramp*		
Speed level	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*
10 mph	10.5	1.1	0.74	10.2	0.6	0.42	10.5	0.3	0.40	10.7	2.0	0.79	10.0	2.0	0.67
15 mph	14.8	2.1	0.83	14.8	2.4	0.89	15.0	0.8	0.50	15.3	2.9	0.73	14.8	2.8	0.76
20 mph	21.0	4.5	1.98	21.5	4.8	2.00[3]	21.5	3.5	1.80	21.5	4.0	1.24	20.5	3.8	1.28
25 mph	26.5	4.5	1.83	25.5	5.0	1.59	26.5	4.4	1.87	26.5	3.6	1.47	27.0	3.2	1.48
Overall average	18.2	3.0	1.34	18.0	3.2	1.22	18.4	2.2	1.14	18.5	3.1	1.06	18.1	3.0	1.05

[1] C ombined results from 12 passengers
[2] Measured with passenger sitting over rear axle
[3] Maximum value for accelerometer (accelerometer on lap of passenger near rear axle)
DR is defined in section 4.2.2

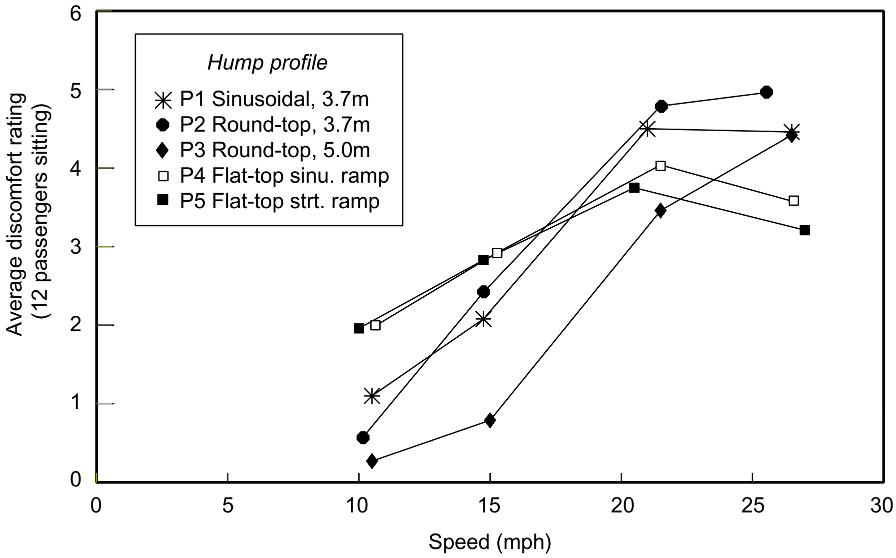


Figure 9a Midibus (Optare Metro Rider)

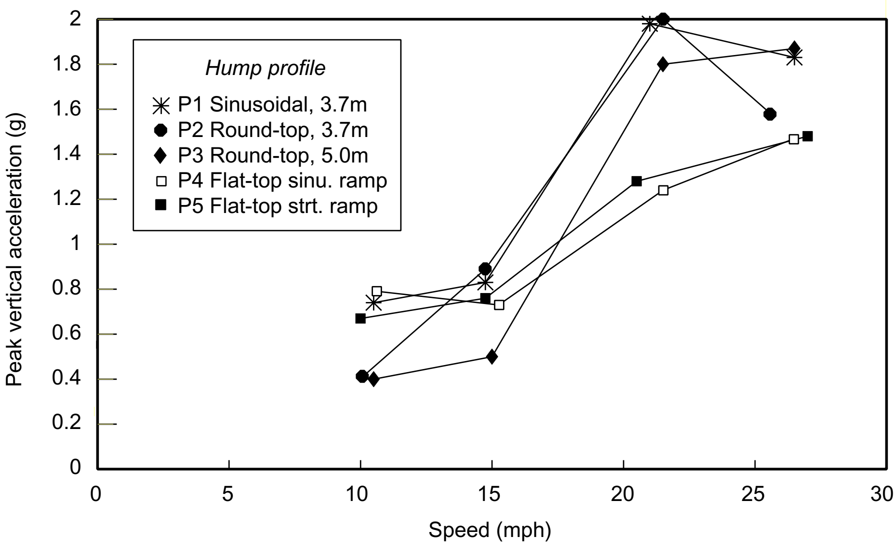


Figure 9b Midibus (Optare Metro Rider)

At 10 mph, the average discomfort ratings for profile P4, *the flat-top hump with sinusoidal ramps*, and profile P5, *the flat-top hump with straight ramps* were about 2 and were higher than the other profiles. The average discomfort ratings for profiles P4 and P5 increased to about 4 at 20 mph but dropped to about 3.5 at 25 mph. As with the minibus, there was generally little difference in discomfort rating between these two profiles.

The results for discomfort rating are supported by those for the peak vertical acceleration of a passenger sitting over the rear axle. At low speeds (10 mph), values of peak vertical acceleration for profiles P1, P2 and P3 were similar to, or lower than, those for profiles P4 and P5. At the higher speeds (20 to 25 mph), values of peak vertical acceleration for profiles P1, P2 and P3 were higher than those for profiles P4 and P5.

In summary, it would seem that, for the midibus, the effect of increase in speed on discomfort rating for the different hump profiles was similar to that for the minibus. As with the minibus, the discomfort rating in the midibus was quite sensitive to changes in vehicle speed over the hump profiles, particularly in the speed range 10 to 20 mph.

At low speeds (about 10 mph) the round-top and sinusoidal profiles P1, P2 and P3 provided less discomfort to passengers in the midibus than the flat-top profiles P4 and P5. However, as speeds increased, the benefit in terms of passenger discomfort provided by profiles P1 and P2 was rapidly reduced such that profiles P4 and P5 provided less discomfort at speeds of 20 to 25 mph. It should be noted that, at speeds of 20 to 25 mph, the values of discomfort rating for all the profiles were relatively high (in the uncomfortable region of the scale) and that such speeds would be deemed unsuitable by bus operators and passengers.

There would be little, if any, benefit in terms of reduced discomfort to midibus passengers in using profile P1, *the 3.7m long sinusoidal hump* rather than profile P2, *the 3.7m long round-top hump*. There would also be little benefit, if any, in using profile P4, *the flat-top hump with sinusoidal ramps*, rather than profile P5, *the flat-top hump with straight ramps*.

5.4.3 Large single deck bus (Optare Low rider)

The average values of speed, discomfort rating and peak vertical acceleration in the large single deck bus (Optare Low Rider) are given in Table 11 and Figures 10a and 10b. Measurements of discomfort rating and vertical acceleration were carried out at speeds from 10 mph to 20 mph. The bus driver declined to cross the flat-top profiles P4 and P5 at 25 mph because he was concerned about possible damage to the bus. Additional runs were carried out at 10 mph and 15 mph with some passengers standing. At 10 mph, the standing passengers reported that it was more uncomfortable than sitting. At 15 mph, the subjects reported that standing was more comfortable than sitting.

Table 11 and Figures 10a and 10b show that, for a given speed, the values of discomfort rating and peak vertical acceleration for sitting passengers in the large single deck bus were generally lower than those for the minibus and midibus. The discomfort ratings for the single deck bus increased with speed from about 0.5 to 1.5 at 10 mph to 1 to 3.5 at 20 mph.

The average discomfort ratings for profile P2, *the 3.7m long round-top hump*, and profile P1, *the 3.7m long sinusoidal hump* started fairly low at about 0.5 at 10 mph and increased steadily to about 3 at 25 mph. There was generally little difference in the values of discomfort rating between these two profiles which were substantially lower than those for the flat-top hump profiles P4 and P5.

The average discomfort rating for profile P3, *the 5m long round-top hump*, started very low (about 0.1) at 10 mph and then increased steadily to about 2.5 at 25 mph. The average discomfort rating for profile P3 was substantially lower than all the other profiles throughout the speed range 10 to 25 mph.

At 10 mph, the average discomfort ratings for profile P4, *the flat-top hump with sinusoidal ramps*, and profile P5, *the flat-top hump with straight ramps* were about 1.5 and were higher than the other profiles. The average discomfort ratings for profiles P4 and P5 increased to about 3.5 at 20 mph. Again, there was generally little difference in discomfort rating between these two profiles.

In the single deck bus, the results for discomfort rating were generally supported by those for vertical acceleration recorded over the rear axle. Values of peak vertical acceleration for profile P3 were generally lower than the other profiles. However, at 25 mph, the peak vertical acceleration for the sinusoidal hump profile P1, was lower than that for the other two profiles P2 and P3 tested at this speed. The results for peak vertical acceleration indicated less difference between profiles P1, P2, P4 and P5 than results for discomfort rating.

In summary, it would seem that the effect of increase in speed on discomfort rating and vertical acceleration for the round-top and sinusoidal hump profiles P1, P2 and P3 was less severe in the large single deck bus than in the midibus. The effect of speed on discomfort rating and vertical acceleration for the flat-top hump profiles P4 and P5 was similar in the midibus and the large single deck bus.

As with the minibus and the midibus, there would be little, if any, benefit in terms of reduced discomfort to passengers in the large single deck bus in using profile P1, *the 3.7m long sinusoidal hump* rather than profile P2, *the 3.7m long round-top hump*. There would also be little benefit, if any, in using profile P4, *the flat-top hump with sinusoidal ramps*, rather than profile P5, *the flat-top hump with straight ramps*. Profile P3, *the 5.0m long round-top hump*, gave the lowest discomfort ratings.

5.4.4 Double deck bus (Optare Spectra)

The average values of speed, discomfort rating, and vertical acceleration in the Optare Spectra double deck bus are given in Table 12 and Figures 11a and 11b. For the double deck bus, six passengers were positioned on the upper deck and six on the lower deck. The passengers took seats on both sides and at the front and back of the bus. Measurements of discomfort rating and vertical acceleration were carried out at speeds from 10 mph to 20 mph. Only one test run was carried out at 25 mph; the driver reported that there was potential for vehicle damage and the trial was stopped at this point.

Table 11 Large single deck bus (Optare Low Rider) — average speed, passenger discomfort rating and peak vertical acceleration

	Average speed, discomfort rating[1] (DR) and peak vertical acceleration[2] (VA)														
	P1 Sinusoidal 3.7m long			*P2 Round-top 3.7m long*			*P3 Round-top 5.0m long*			*P4 Flat-top sinusoidal ramp*			*P5 Flat-top straight ramp*		
Speed level	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*
10 mph	10.2	0.3	0.48	10.5	0.5	0.42	10.0	0.1	0.28	10.0	1.3	0.60	10.2	1.3	0.51
15 mph	15.1	1.6	0.73	14.3	1.2	0.60	15.0	0.6	0.45	14.8	2.4	0.71	14.3	2.5	0.67
20 mph	20.0	1.8	0.99	20.0	2.1	0.92	20.0	1.2	0.65	20.5	3.7	1.02	20.5	3.3	0.97
25 mph	25.5	3.4	1.11	25.0	3.0	1.49	26.0	2.5	1.33	n/t	n/t	n/t	n/t	n/t	n/t
Overall average	17.7	1.8	0.82	17.5	1.7	0.86	17.8	1.1	0.67	n/a	n/a	n/a	n/a	n/a	n/a

[1] Combined results from 12 passengers

[2] Measured with passenger sitting over rear axle (accelerometer on lap of passenger near rear axle)

n/t not tested at this speed due to possible damage to bus; n/a not applicable

DR is defined in section 4.2.2

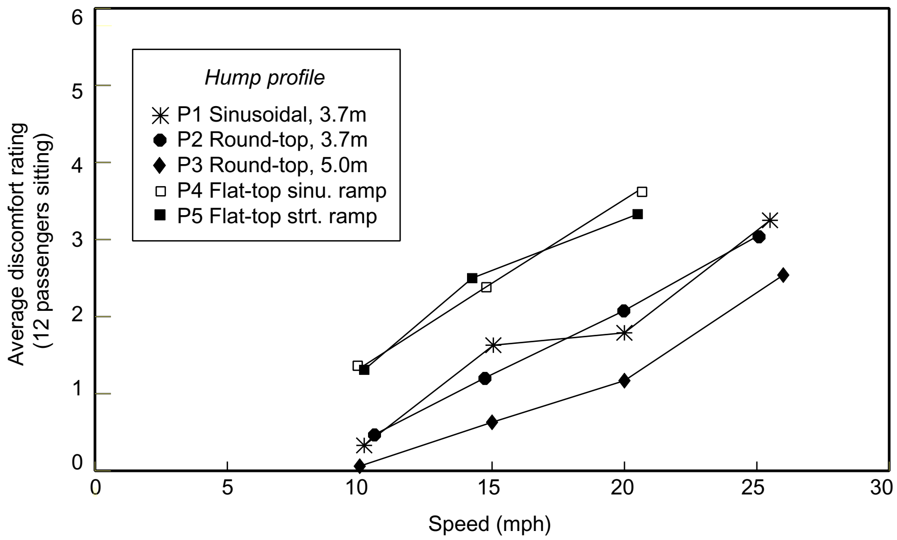


Figure 10a Large single-deck bus (Optare Low Rider)

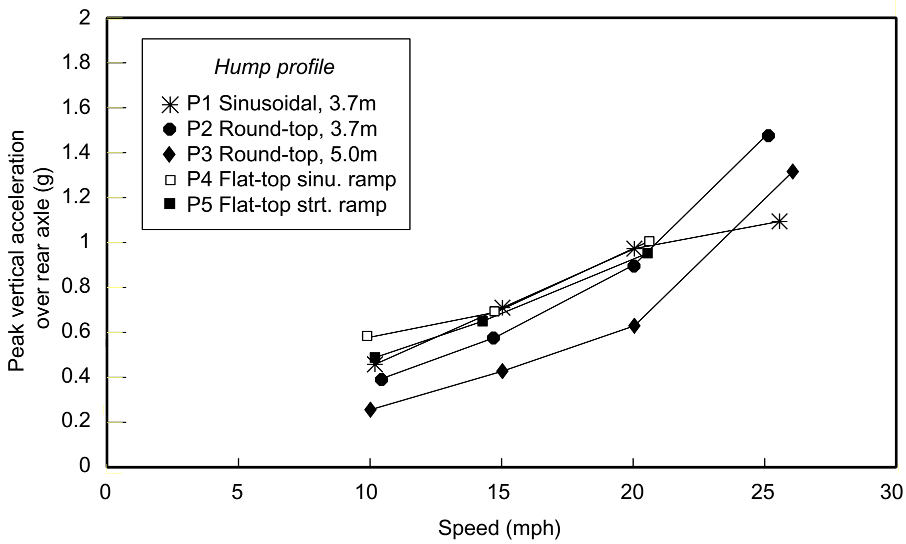


Figure 10b Larged single-deck bus (Optare Low Rider)

Table 12 Double deck-bus (Optare Spectra) — average speed, passenger discomfort rating and peak vertical acceleration

	Average speed, discomfort rating[1] (DR) and peak vertical acceleration[2] (VA)														
	P1 Sinusoidal 3.7m long			*P2 Round-top 3.7m long*			*P3 Round-top 5.0m long*			*P4 Flat-top sinusoidal ramp*			*P5 Flat-top straight ramp*		
Speed level	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*	*Speed (mph)*	*DR*	*VA (g)*
10 mph	9.0	0.9	0.48	9.0	0.5	0.37	9.0	0.2	0.22	9.3	0.6	0.40	9.3	1.2	0.43
15 mph	14.0	2.2	0.53	13.5	1.6	0.60	14.5	1.6	0.58	14.0	2.3	0.54	14.0	2.0	0.44
20 mph	19.0	4.2	1.54	18.0	4.5	1.92	18.0	3.9	1.39	19.0	3.8	1.02	19.0	3.8	0.89
25 mph	n/t	n/t	n/t	n/t	n/t	n/t	n/t	n/t	n/t	n/t	n/t	n/t	n/t	n/t	n/t
Overall average	14.0	2.4	0.96	13.5	2.2	0.96	13.8	1.7	0.73	14.1	2.2	0.52	14.1	2.3	0.59

[1] Combined results from 12 passengers
[2] Measured with passenger sitting over rear axle (accelerometer on lap of passenger near rear axle)
n/t not tested at this speed due to possible damage to bus; DR is defined in section 4.2.2

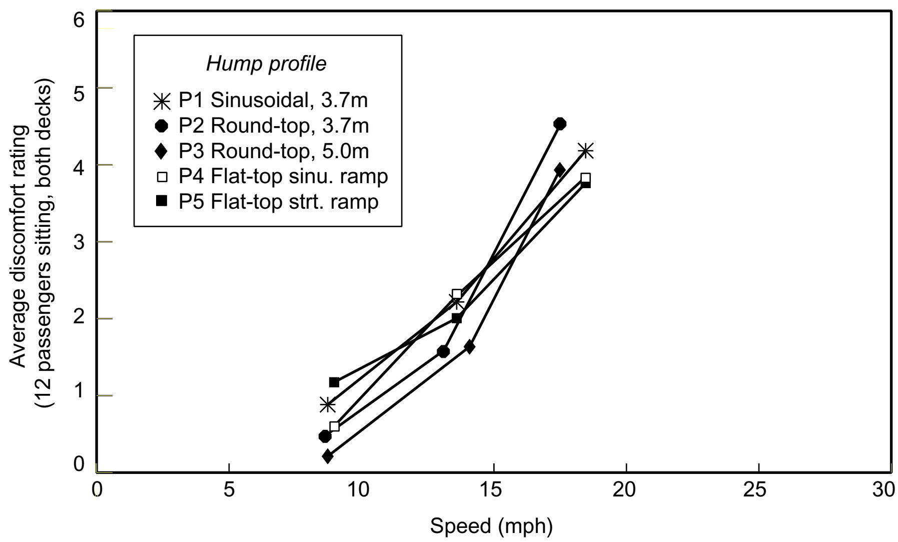


Figure 11a Double-deck bus (Optare Spectra)

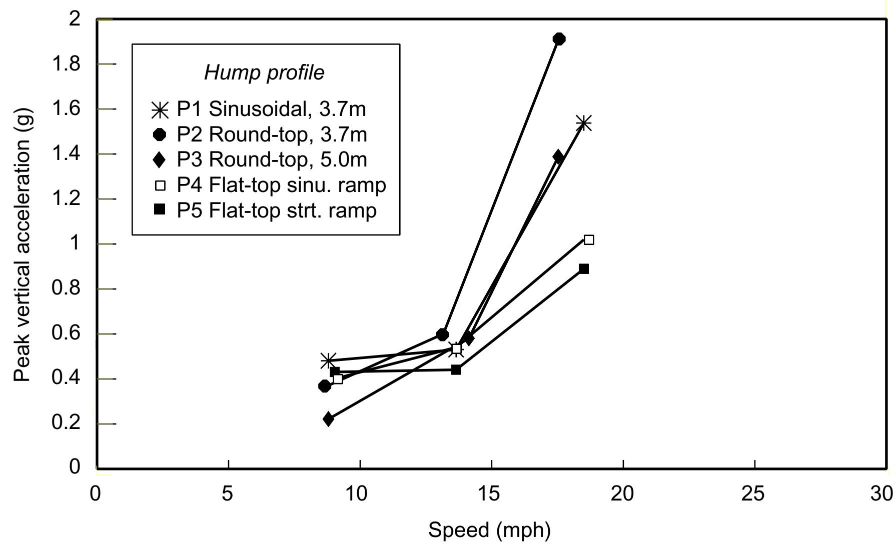


Figure 11b Double-deck bus (Optare Spectra)

In a second set of runs at 15 mph, passengers who had been upstairs were swapped with passengers downstairs. The results of these runs indicated that discomfort increased from the front to the back of the bus and from downstairs to upstairs; downstairs at the front tended to be the most comfortable position and upstairs at the back the least comfortable. The greatest level of discomfort felt when the bus was coming off the humps.

The average discomfort ratings recorded in the double-deck bus increased with speed from about 0.5 to 1 at 10 mph, to about 4 at 20 mph. There was less difference between the discomfort ratings for the different hump profiles for the double-deck bus than for the other buses. The round-top hump profiles P2 and P3 gave slightly lower discomfort ratings than the other profiles at speeds of 10 mph and 15 mph but the flat-top profiles P4 and P5 had slightly lower values of discomfort rating at 20 mph.

The effect of increase in speed on discomfort rating and vertical acceleration for the hump profiles was more severe in the double deck bus than in the large single deck bus and, in this respect the results for the double deck bus, were more similar to those of the midibus. Values of vertical acceleration recorded for a passenger sitting over the rear axle in the double deck bus increased rapidly from about 0.5g at 14 mph to about 1.5g to 1.9g at 18 mph for the round-top and sinusoidal profiles P1, P2 and P3. The increase was less marked for the flat-top profiles, P4 and P5 with values of about 0.9g to 1.0g at 19 mph.

As with the other buses, there would be little, if any, benefit in terms of reduced discomfort to passengers in the large single deck bus in using profile P1, *the 3.7m long sinusoidal hump* rather than profile P2, *the 3.7m long round-top hump*. There would also be little benefit, if any, in using profile P4, *the flat-top hump with sinusoidal ramps,* rather than profile P5, *the flat-top hump with straight ramps*.

5.4.5 Discussion of results for bus passengers

The average discomfort rating experienced by sitting passengers in the four types of bus when crossing the profiles at speeds of 15 mph and 20 mph are shown in Figures 12a and 12b. These speeds have been chosen as they represent speeds that might be experienced when crossing humps on the public roads. The results in Figure 12 illustrate how a small change in speed can lead to a large increase in discomfort for bus passengers.

At speeds of about 15 mph, the average discomfort ratings for all the bus types tested were between about 0.5 and 3.5. Profile P3 generally gave the lowest discomfort ratings and profiles P4 and P5 the highest discomfort ratings. There was less variation in discomfort rating across the different profiles for the double-deck bus than for the other bus types.

At speeds of about 20 mph, the average discomfort ratings increased substantially for passengers in the minibus, midibus and double-deck bus, particularly when crossing the round-top and sinusoidal profiles, P1, P2 and P3. The average discomfort ratings were in the range 3.5 to 5 for passengers in the minibus and midibus, 3.8 to 4.5 for passengers in the double-deck bus and 1.2 to 3.7 for passengers in the single-deck bus. Profile P3 gave the lowest discomfort ratings for the minibus, the midibus and the single-deck bus. Profiles P1 and P2 gave the highest discomfort ratings for the minibus, the midibus and the double-deck bus. Again there was less variation in discomfort rating across the different profiles for the double-deck bus than for the other bus types.

The results suggest that driving buses over flat-top or round-top hump profiles at speeds over 15 mph is likely to cause unnecessary discomfort to bus passengers. Where possible, bus operators should try to encourage drivers to cross humps at speeds of 15 mph or less. For some combinations of bus type and hump profile a steady speed of 15 mph may be appropriate along roads where road humps are present. At speeds of 15 mph or less the round-top and sinusoidal profiles generally gave less discomfort than the flat-top hump profiles. It was only at the higher speeds of 20 mph or more, where the level of discomfort is not generally acceptable, that the situation changes and the flat-top humps gave similar or lower discomfort for passengers in the minibus, the midibus and the double-deck bus.

5.5 Commercial vehicles

Three commercial vehicles were used in the track trials (all unladen): a 38 tonne articulated tipper lorry with air suspension, a 38 tonne articulated tipper lorry with steel suspension, and a 17 tonne dropside lorry with a rigid body and steel suspension.

The average discomfort ratings reported by the drivers of these commercial vehicles when crossing the profiles at different speeds are shown in Figures 13a, 13b and 13c. Runs were not undertaken with the two 38 tonne lorries at speeds greater than 16 mph for profile P2, and speeds greater than 19 mph for the other profiles, because of concern about discomfort, vehicle damage or loss of control at higher speeds. For the 17 tonne lorry, runs were carried out for all profiles at speeds up to about 28 mph. At speeds of 25 mph and above, the wheels of the 17 tonne lorry were seen to lift off the ground when traversing profiles P1 and P2.

For the two 38 tonne articulated tipper lorries, Figures 13a and 13b show that, as speeds increased from about 10 mph to about 20 mph, the average discomfort ratings rose very sharply for all five profiles from low levels of 0 to 1 to high levels of about 5 to 6. There was little consistent difference in discomfort rating between the different profiles. For the 38 tonne vehicle with air suspension, profile P4, *the flat-top with sinusoidal ramps,* gave the highest discomfort ratings at speeds of 10 to 15 mph, and profile P3, *the round-top 5.0m long,* gave the lowest discomfort ratings at speeds over 15 mph. For the 38 tonne vehicle with steel suspension, profile P5, *the flat-top with straight ramps,* gave the highest discomfort ratings at the lower speeds.

Figure 13c shows that the rise in average discomfort ratings was less steep over the 10 to 20 mph speed range for the 17 tonne lorry with a rigid body than it was for the two 38 tonne articulated lorries. The discomfort ratings for the 17 tonne vehicle were higher than those for the 38

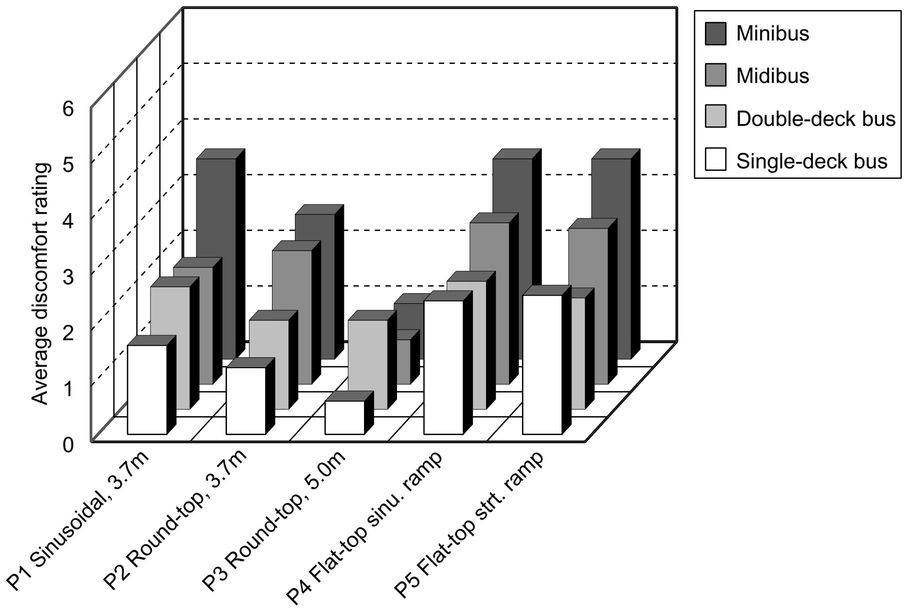


Figure 12a Minibus, midibus, double-deck bus and single-deck bus at 15 mph

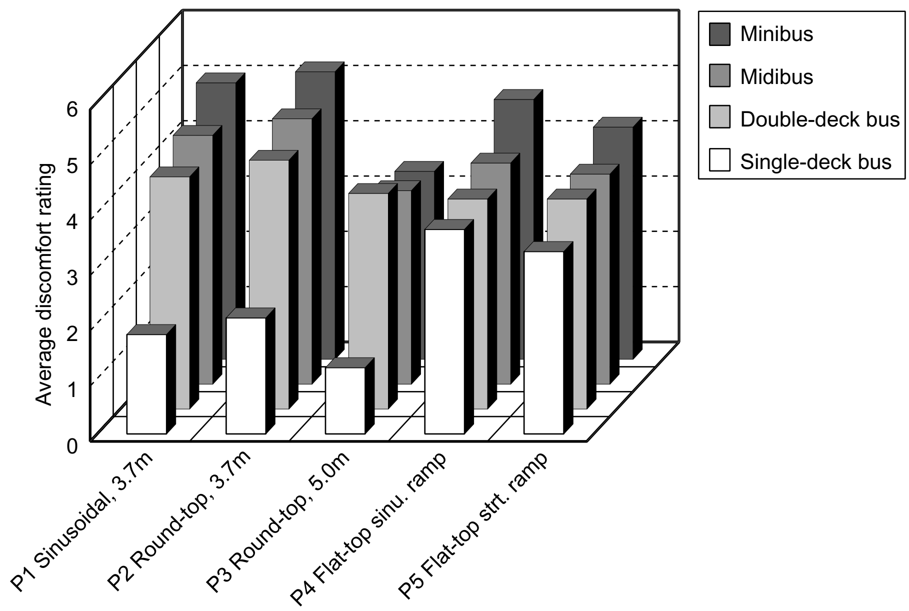


Figure 12b Minibus, midibus, double-deck bus and single-deck bus at 20 mph

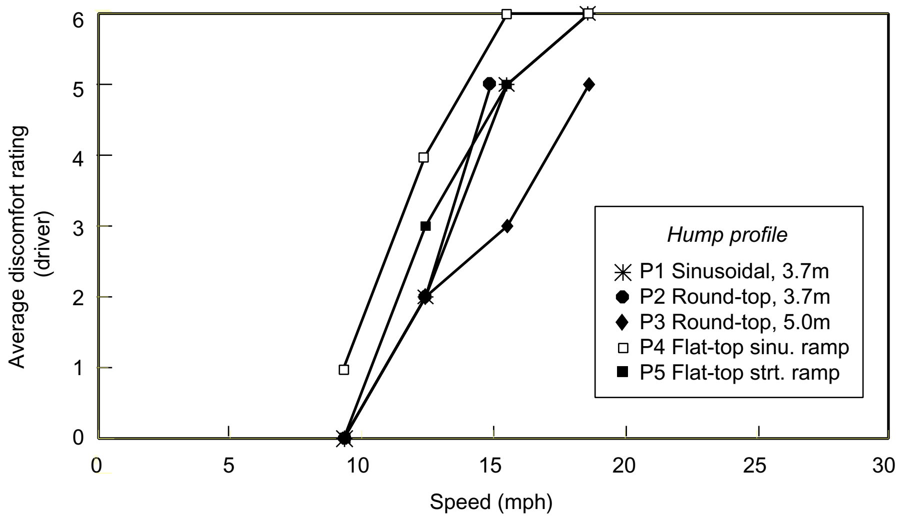


Figure 13a 38 tonne unladen articulated tipper lorry — air suspension

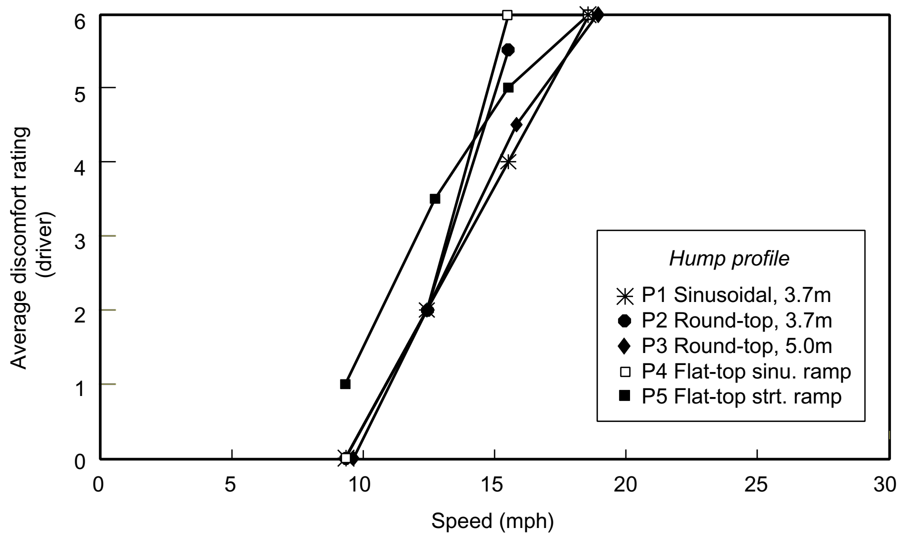


Figure 13b 38 tonne unladen articulated tipper lorry — steel suspension

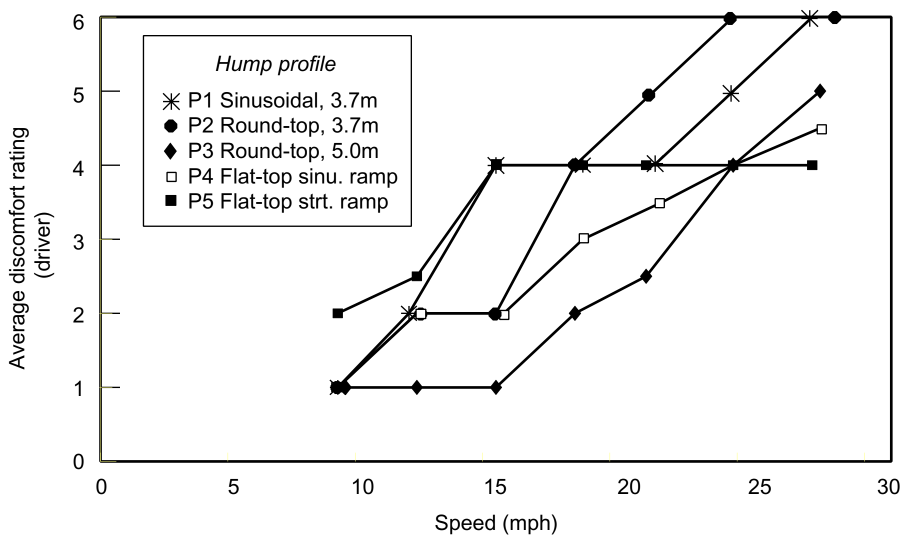


Figure 13c 17 tonne unladen dropside lorry, rigid body, steel suspension

tonne articulated vehicles at 9 mph but lower at higher speeds. Profile P3, *the 5.0m long round-top,* gave the lowest discomfort ratings for the 17 tonne vehicle across most of the speed range tested. Profile P5, *the flat-top with straight ramps*, gave the highest discomfort ratings in the speed range 10 to 15 mph, while profile P2, *the 3.0m long round-top*, gave the highest discomfort ratings in the speed range 20 to 25 mph.

5.6 Emergency service vehicles

Four emergency service vehicles were used in the track trials: a Dennis RS fire appliance, a GMC Chevrolet ambulance, a Ford Transit ambulance, and an Iveco Turbo Daily 40-10 ambulance.

5.6.1 Fire appliance

The average values of speed, discomfort rating, and vertical acceleration in the

Dennis RS fire appliance are shown in Figures 14a and 14b. Three crew members rode in the fire appliance during the trials and reported their assessment of discomfort. The accelerometer was strapped to the lap of one of the crew.

The fire appliance travelled over the hump profiles at speeds of about 10 and 15 mph. Measurements at speeds above 15 mph were not carried out as a trial run at 20 mph caused some damage to the vehicle and its equipment.

Figures 14a and 14b show that as the speed increased from about 10 mph to about 15 mph, the average discomfort ratings and vertical acceleration increased. The vertical acceleration measured when crossing profile P3, *the 5.0m long round-top*, was substantially lower than when crossing the other profiles, particularly at speeds of about 15 mph. The discomfort rating for profile P3 was also lower than most of the other profiles at about 2 to 2.5.

There was more discrimination between the other profiles for discomfort rating than for vertical acceleration but the ranking order was similar with both parameters. The flat-top profiles P4 and P5 generally gave the highest discomfort ratings at about 3.5 to 6. Profile P2, *the 3.7m long round-top*, and profile P1, *the 3.7m long sinusoidal hump,* gave slightly lower discomfort rating at about 2 to 5.

As with many of the other vehicle types tested, the results in Figures 14a and 14b indicate that there would be little, if any, benefit in terms of reduced discomfort to crew in the fire appliance in using profile P1, *the 3.7m long sinusoidal hump* rather than profile P2, *the 3.7m long round-top hump*. There would also be little benefit, if any, in using profile P4, *the flat-top hump with sinusoidal ramps*, rather than profile P5, *the flat-top hump with straight ramps.*

5.6.2 Ambulances

Figures 15a, 15b and 15c show the average values of speed over the different hump profiles and the discomfort rating recorded by passengers sitting in the rear of the three ambulances (a Ford Transit, an Iveco Turbo Daily 40-10, and a GMC Chevrolet) in a position normally occupied by a casualty. In the GMC Chevrolet ambulance, discomfort was also recorded by an observer who was lying on the ambulance bed.

Measurements of discomfort rating were carried out at speeds from 10 mph to 25 mph. No major problems with vehicle handling were reported by the drivers but they all found that their vehicles became more bouncy as the speed increased. The driver of the Iveco Turbo Daily 40-10 reported that the handling was difficult when crossing profile P5 at 10 mph and the driver of the Ford Transit reported that the vehicle grounded when crossing P2 at 20 mph.

The change in discomfort rating with speed for the passengers in the ambulances was generally similar to results recorded in the minibus and the midibus. At low speeds (about 10 mph) the round-top and sinusoidal profiles P1, P2 and P3 provided less discomfort to passengers in the ambulances than the flat-top profiles P4 and P5. However, as speeds increased, the benefit in terms of passenger discomfort provided by profiles P1 and P2 was rapidly reduced, such that profiles P4 and P5 provided similar or less discomfort at speeds of 15 mph and over. At speeds of 10 to 15 mph, the lowest discomfort ratings were given by profile P3, *the round-top 5.0m long*. At the higher speeds, the values of discomfort rating provided by the flat-top profiles, P4 and P5, were less than, or similar to, those of profile P3.

The results for the GMC Chevrolet ambulance were slightly different from those of the other two. The discomfort rating for profile P5, *the flat-top hump with straight ramps*, was higher than the other profiles at 10 mph but, for this profile, the discomfort rating decreased with increasing speed and gave the lowest discomfort rating at 20 to 25 mph.

As with many of the other vehicle types tested, the results in Figure 15 indicate that there would be little, if any, benefit in terms of reduced discomfort to passengers in the ambulances in using profile P1, *the 3.7m long sinusoidal hump* rather than profile P2, *the 3.7m long round-top hump*. There would also be little benefit, if any, in using profile P4, *the flat-top hump with sinusoidal ramps,* rather than profile P5.

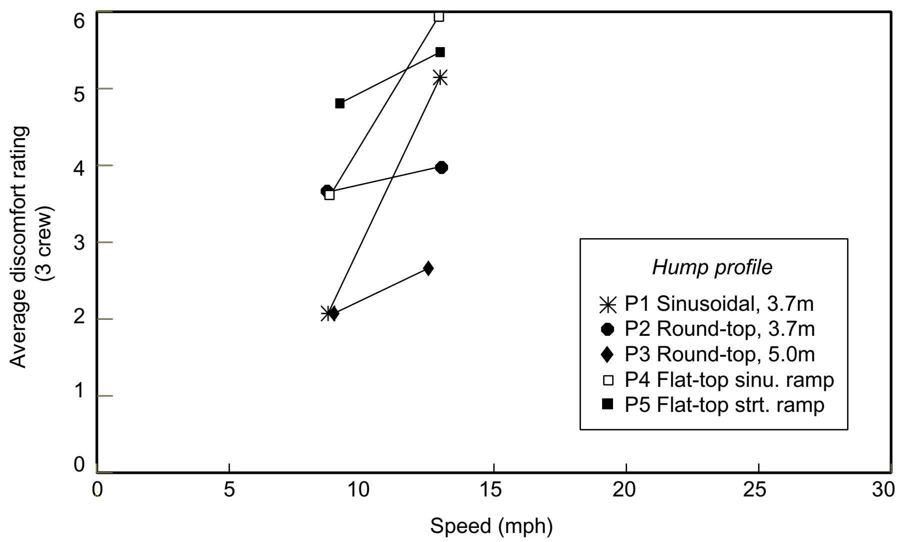


Figure 14a Fire appliance (Dennis RS)

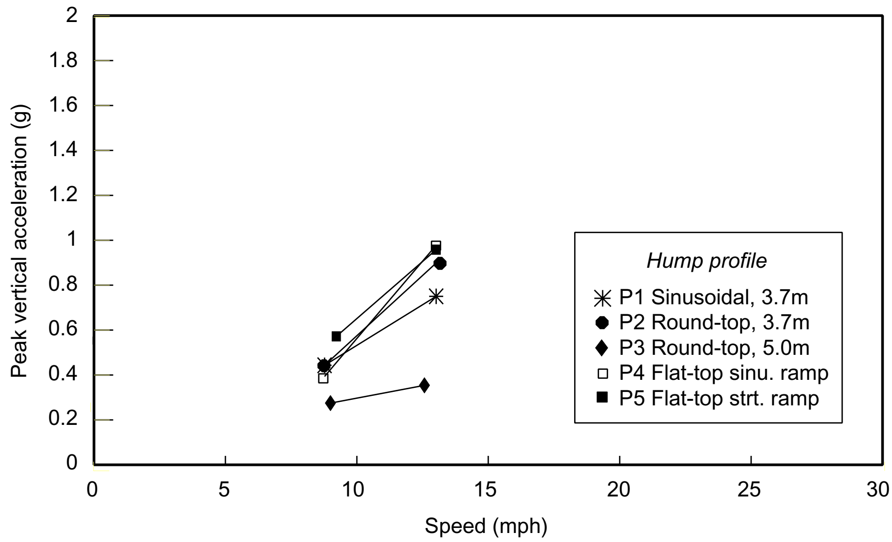


Figure 14b Fire appliance (Dennis RS)
(accelerometer on lap of crew)

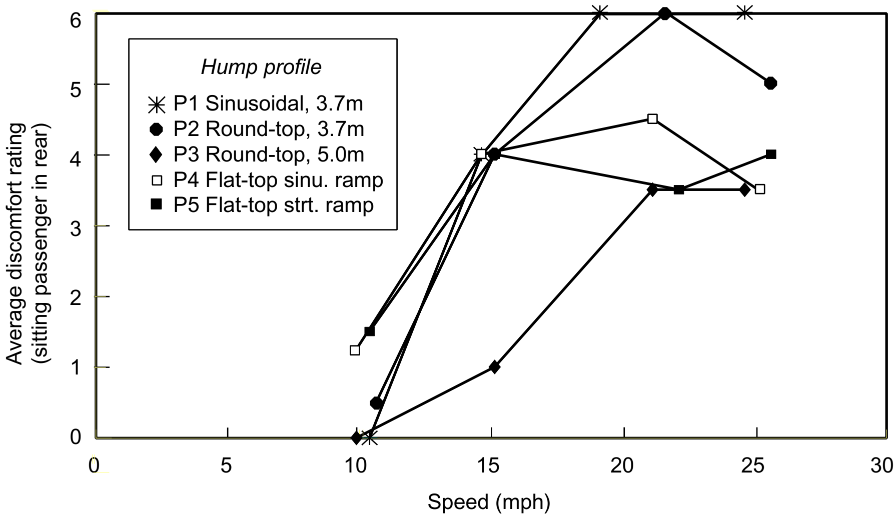


Figure 15a Ambulance (Ford Transit — Devon conversion)

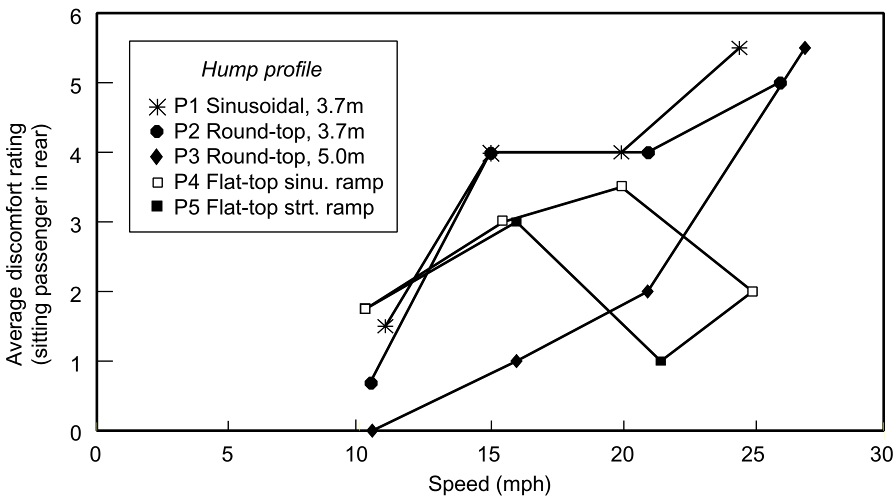


Figure 15b Ambulance (Iveco Turbo Daily 14–10)

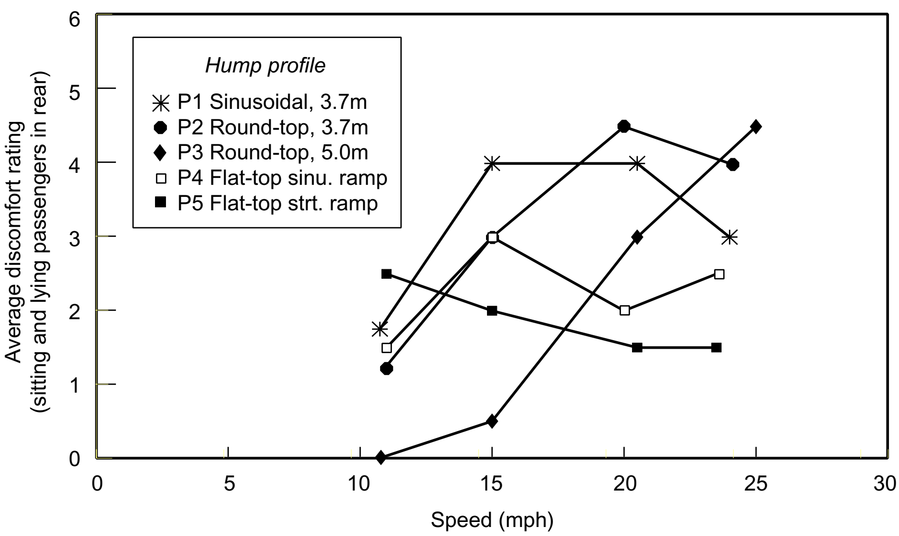


Figure 15c Ambulance (GMC Chevrolet)

6 Conclusions

The five hump profiles used in the trials included three profiles not commonly used in Great Britain: a 3.7m long hump with a sinusoidal profile (P1), a 5m long round-top hump (P3), and an 8m long flat-top hump with sinusoidal ramps (P4). Two 'standard' profiles were included for comparison: a 3.7m long round-top hump (P2) and an 8m long flat-top hump with straight ramps (P5). All the hump profiles were 75mm high.

Sinusoidal hump, 75mm high, 3.7m long - (P1)

1 The 3.7m long sinusoidal profile P1 gave less discomfort to cyclists than the equivalent 'standard' 3.7m long round-top profile P2. However, the difference in discomfort was not large.

2 There was a slight benefit in terms of discomfort to car passengers in the use of the sinusoidal profile P1 compared to the round-top profile P2 but there was little, if any, benefit to motor cycle riders, bus passengers, commercial vehicle drivers, fire crew and ambulance passengers. It is likely that the speed reduction achieved by the use of the sinusoidal profile P1 on the public roads would be similar to that achieved by the round-top profile P2. The companion TRL Report TRL416 indicates that maximum noise and ground-borne vibration levels generated by the passage of heavy commercial vehicles are likely to be slightly less with the sinusoidal profile P1 than with the round-top profile P2. However, the results for the double-deck bus that was tested were less consistent with lower maximum noise levels, but higher ground-borne vibration levels, with profile P1 than with profile P2.

3 Some cyclists taking part in the tests said while there were differences in discomfort between the different hump profiles tested it was noticeable that the test humps had been constructed so there was no upstand or discontinuity where the humps met the road surface. Such upstands are often present at humps on the public road and are likely to increase the discomfort experienced by cyclists. It may be more important for the local authority to ensure that humps have no upstand than whether humps have a round-top or sinusoidal profile.

4 Depending on the method of hump construction used in hump schemes on the public roads, there may be extra difficulty/expense in constructing the sinusoidal profile rather than a round-top profile and this would need to be taken into account when deciding which hump profile was appropriate.

5 Other traffic calming measures such as speed cushions (vertical deflections which do not span the whole carriageway) and chicanes (horizontal deflections) do not generally cause cyclists discomfort. Like most traffic calming measures, including road humps, these measures have some operational problems and are not appropriate in all situations. However, their use should be considered when selecting traffic calming measures on routes used by substantial numbers of cyclists. It should be noted that cycle bypass lanes are recommended at chicane sites and other road narrowings because of concerns about conflicts between cyclists and overtaking traffic.

6 Most riders and drivers reported no vehicle handling problems when crossing the sinusoidal profile P1 at speeds within the range tested. However, the midibus was reported as difficult to handle when crossing P1 at speeds of 20 and 25 mph. The maximum speed tested was limited to about 15 mph for the fire appliance, and 20 mph for the double-deck bus and the 38 tonne articulated lorry because of concerns about severe discomfort, vehicle damage or vehicle handling.

Flat-top hump with sinusoidal ramps, 75mm high, 6m plateau, 1m ramps - (P4)

7 There was little, if any, benefit in terms of discomfort to any of the riders or vehicle occupants in the use of the flat-top profile with sinusoidal ramps P4 compared to the equivalent 'standard' flat-top profile with straight ramps P5. It is likely that the speed reduction achieved by the use of the flat-top profile with sinusoidal ramps P4 on the public roads would be similar to that achieved by the flat-top profile with straight ramps P5. The companion TRL Report TRL416 indicates that maximum noise and ground-borne vibration levels generated by the passage of buses and heavy commercial vehicles are likely to be less with the flat-top profile with sinusoidal ramps P4 than with the flat-top profile with straight ramps P5.

8 Profiles P4 and P5 gave the most discomfort for cyclists. In order to reduce discomfort to cyclists, the results indicate that the use of flat-top humps profiles on routes used by substantial numbers of cyclists should be avoided except at humped pedestrian crossings where a flat surface is required.

9 Most riders and drivers reported no vehicle handling problems when crossing profile P4 at speeds within the range tested. However, some cyclists were concerned about a potential loss of control when reaching the bottom of the off ramps, particularly when crossing at higher speeds. The midibus driver reported that the bus grounded momentarily at 20 mph. The maximum speed tested was limited to about 15 mph for the fire appliance, and 20 mph for the single-deck bus, the double-deck bus and the 38 tonne articulated lorry because of concerns about severe discomfort, vehicle damage or vehicle handling.

Round-top hump, 75mm high, 5.0m long - (P3)

10 The 5m long round-top profile P3 gave the lowest values of discomfort, throughout most of the speed range tested, to cyclists, motor cycle riders and car passengers. Also, it gave the lowest values of discomfort, at speeds of 10 to 15 mph, for bus passengers, fire crew and ambulance passengers.

11 At higher speeds of 20 to 25 mph, the flat-top profiles P4 and P5 generally gave similar or lower values of discomfort for bus passengers and ambulance

passengers than profile P3. However, it should be noted that at speeds of 20 to 25 mph, the values of discomfort rating for all profiles recorded by passengers in most of the buses and ambulances tested were relatively high (in the uncomfortable region of the scale) and it is likely that such speeds would be considered unsuitable by the operators and passengers.

12 The use of the 5m long round-top profile P3 on the public roads rather than the more commonly used ‘standard’ profiles, the 3.7m long round-top P2, or the flat-top with straight ramps P5, would reduce discomfort for drivers, riders and passengers if travelling at similar speeds to those that occur in practice with humps of type P2 and P5. However, it is likely that car drivers on the public roads would increase speed to bring the discomfort experienced at profile P3 in line with that experienced at profiles P2 and P5. Mean crossing speeds for cars at profile P3 are therefore likely to be about 20 to 25 mph, compared to about 15 mph at profiles P2 and P5.

13 The speed reduction achieved with hump profile P3 would be less than that achieved with profiles P2 or P5. However, profile P3 might be suitable where it was desired to control speeds to below 30 mph rather than to below 20 mph. Any benefit to passengers in buses and ambulances in terms of reduced discomfort would require bus and ambulance drivers to keep their speeds low rather than take advantage of the lower levels of discomfort to increase speed. The companion TRL Report TRL416 indicates that maximum noise and ground-borne vibration levels generated by the passage of buses and heavy commercial vehicles over the 5m long round-top profile P3 are likely to be similar to those generated over the 3.7m long round-top profile P2.

14 Most riders and drivers reported no vehicle handling problems when crossing profile P3 at speeds within the range tested. The maximum speed tested was limited to about 15 mph for the fire appliance, and 20 mph for the double-deck bus and the 38 tonne articulated lorry because of concerns about severe discomfort, vehicle damage or vehicle handling.

Round-top hump, 75mm high, 3.7m long - (P2) and flat-top hump with straight ramps, 75mm high, 6m plateau, 1m ramps - (P5)

15 The 3.7m long round-top profile P2 gave lower values of discomfort than the flat-top profile with straight ramps P5 throughout most of the speed range tested for cyclists, motor cycle riders and car passengers. Profile P2 also generally gave lower values of discomfort than P5 for the motor cycle combination, bus passengers, commercial vehicle drivers, fire crew and ambulance passengers when travelling at speeds of 10 to 15 mph. However, at speeds above 15 mph, the round-top profile P2 generally gave similar or higher values of discomfort for these vehicle types than the flat-top profile P2.

16 Above 20 mph the discomfort experienced by car occupants when travelling over profile P5, increased more rapidly with speed than that for profile P2. Thus the flat-top profile P5 might be more suitable than the round-top profile P2 at discouraging car drivers who might otherwise drive at these higher speeds. However, a general use of the flat-top hump profile P5 rather than the round-top profile P2, for controlling car speeds to below 20 mph, would increase discomfort for cyclists, for passenger in buses (at speeds below 20 mph), and for passengers in ambulances (at speeds below 15 mph). The companion TRL Report TRL416 indicates that the use of the flat-top profile P5 rather than the round-top profile P2 would also increase the noise and ground-borne vibrations generated by the passage of buses and heavy commercial vehicles. On bus routes and routes commonly used by the emergency services and commercial traffic, other traffic calming measures, such as narrow speed cushions which generally give less discomfort and cause less delay than road humps, are possibly more appropriate.

17 Most riders and drivers reported no vehicle handling problems when crossing profiles P2 and P5 at speeds within the range tested. The maximum speed tested was limited to about 15 mph for the fire appliance, and 20 mph for the single-deck bus (P5 only), the double-deck bus and the 38 tonne articulated lorry because of concerns about severe discomfort, vehicle damage or vehicle handling. The midibus driver reported that the bus grounded momentarily when crossing the round-top profile P2 at 15 mph and the driver of the Ford Transit ambulance reported that the ambulance grounded when crossing P2 at 20 mph. The midibus was reported as difficult to handle when crossing P2 at speeds of 20 and 25 mph. As with the other flat-top profile P4, some cyclists were concerned about a potential loss of control when crossing profile P5. The drivers of the midibus and Iveco Turbo ambulance reported that the handling of their vehicles was difficult when crossing profile P5 at 10 mph.

The discomfort experienced by bus passengers substantially increased as speeds across the hump profiles increased from 15 to 20 mph. Driving buses on the public roads at speeds over 15 mph across sinusoidal, round-top or flat-top profiles of the types tested is likely to cause unnecessary discomfort to bus passengers. Bus operators should try to encourage drivers to cross such hump profiles at speeds of 15 mph or less to minimise discomfort. For some combinations of bus type and hump profile a steady speed of 15 mph might be appropriate along roads where road humps are present.

7 Acknowledgements

The authors would like to thank the people who took part in the trials as drivers, riders or passengers and the individuals and organisations that supplied the vehicles including: Reading Transport for the buses, The Royal Berkshire Ambulance Trust, the Royal Berkshire Fire and Rescue Service and Mr Sallsbury of the Portsmouth and District Sidecar club for the motor cycle and sidecar combination. Thanks are also due to TRL Engineering Services who supervised the hump construction and to the TRL staff who assisted in the organisation of the trials.

8 References

Baguley C J (1981). *Speed control humps - Further public road trials.* Laboratory Report LR1017, Transport Research Laboratory, Crowthorne.

CROW (1998). *ASVV Manual - Recommendations for traffic provisions in built-up areas.* CROW Record 15, CROW, PO Box 37, NL-6710 BA EDE, Netherlands.

Danish Road Directorate (1991). *Urban Traffic Areas, Part 7 - Speed reducers.* Road Data Laboratory, Copenhagen, Denmark.

Department of Transport (1983). *Road humps.* Circular Roads 5/83, Department of the Environment, Transport and the Regions, London.

Department of Transport (1986). *Road humps.* Circular Roads 8/86, Department of the Environment, Transport and the Regions, London.

Department of Transport (1990). *Speed control humps.* Traffic Advisory Leaflet 2/90. Traffic Advisory Unit, London.

Department of Transport (1993). *Traffic calming special authorisations.* Traffic Advisory Leaflet 3/93. Traffic Advisory Unit, London.

Department of Transport (1994). *Fire and ambulance services traffic calming: A code of practice.* Traffic Advisory Leaflet 3/94. Traffic Advisory Unit, London.

Department of Transport (1996). *Highways (Road Humps) Regulations 1996.* Traffic Advisory Leaflet 7/96. Traffic Advisory Unit, London.

Department of Transport (1997). *Cyclists at road narrowings.* Traffic Advisory Leaflet 1/97. Traffic Advisory Unit, London.

Department of Environment, Transport and the Regions (1997). *Chicane schemes.* Traffic Advisory Leaflet 12/97. Traffic Advisory Unit, London.

Department of Environment, Transport and the Regions (1998). *Speed cushion schemes.* Traffic Advisory Leaflet 1/98. Traffic Advisory Unit, London.

De Wit T and Slop M (1984). *Traffic humps as recommended by SVT: Design and effects.* PTRC Summer Meeting at University of Sussex, July, 1984.

De Wit T (1993). *Dutch experiences with speed control humps.* ITE 63rd Annual Meeting, 1993 The Hague.

Harris G J, Stait R E, Abbott P G and Watts G R (1999). *Traffic calming: vehicle generated noise and ground-borne vibration alongside sinusoidal, round-top and flat-top humps.* TRL Report TRL416. Transport Research Laboratory, Crowthorne.

Hodge A R (1993). *Speed control humps - A trial at TRL.* Project Report PR32. Transport Research Laboratory, Crowthorne.

Kjemtrup K (1990). *Speed reducing measures.* Conference paper, Copenhagen 4/1990.

Lahrmann H and Mathiasen P (1992). *Bumpudformning. (Hump design).* Dansk Vejtidsskrift Nr 9, pp16 - 22. (In Danish).

Layfield R E and Parry D I (1998). *Traffic calming - Speed cushion schemes.* TRL Report TRL312. Transport Research Laboratory, Crowthorne.

Lines C J and Castelijn H A (1991). *Translation of Dutch 30 kph zone design manual.* Published Article PA2046/91. Transport Research Laboratory, Crowthorne.

Moses P J (1992). *Traffic management in New Zealand - 1991 - A perspective.* Main Roads Department, East Perth, Western Australia.

Statutory Instrument 1999 No. 1025. The Highways (Road Humps) Regulations 1999. Stationery Office, London

Sumner R and Baguley C (1979). *Speed control humps on residential roads.* Laboratory Report LR878, Transport Research Laboratory, Crowthorne.

Watts G R (1973). *Road humps for the control of vehicle speeds.* Laboratory Report LR597. Transport Research Laboratory, Crowthorne.

Webster D C (1993). *Road humps for controlling vehicle speeds.* Project Report PR18. Transport Research Laboratory, Crowthorne.

Webster D C and Mackie A M (1996). *Review of traffic calming schemes in 20 mph zones.* TRL Report TRL215. Transport Research Laboratory, Crowthorne.

Webster D C and Layfield R E (1996). *Traffic calming - Road hump schemes using 75 mm high humps.* TRL Report TRL186. Transport Research Laboratory, Crowthorne.

Webster D C and Layfield R E (1998). *Traffic calming - Sinusoidal, 'H' and 'S' humps.* TRL Report TRL377. Transport Research Laboratory, Crowthorne.

Appendix A: Photographs of hump profiles and hump construction

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 6 Construction of hump profiles, filling the formers with pre mixed concrete

Plate 7 Construction of hump profiles, first half of hump compacted and leveled

Appendix B: Photographs of vehicles tested

Plate 8 Cyclist riding a folding bicycle with small wheels over profile P1

Plate 9 Cyclist riding a touring bicycle over profile P3

Plate 10 Cyclist riding a hybrid mountain/road bicycle over profile P5

Plate 11 Honda VFR 750cc motor cycle

Plate 12 BMW R80 800cc motor cycle and Squire side-car

Plate 13 Ford Fiesta

Plate 14 Ford Escort

Plate 15 Ford Mondeo

Plate 16 Optare City Pacer minibus
2000 series

Plate 17 Optare Metro Rider midibus 600 series

Plate 18 Optare Low Rider single-deck bus

Plate 19 Optare Spectra double-deck bus (DAF)

Plate 20 38 tonne ERF EC10 tractor and tri-axle trailer, steel suspension

Plate 21 38 tonne Leyland DAF 95 tractor and tri-axle trailer, air suspension

Plate 22 Dennis RS fire appliance

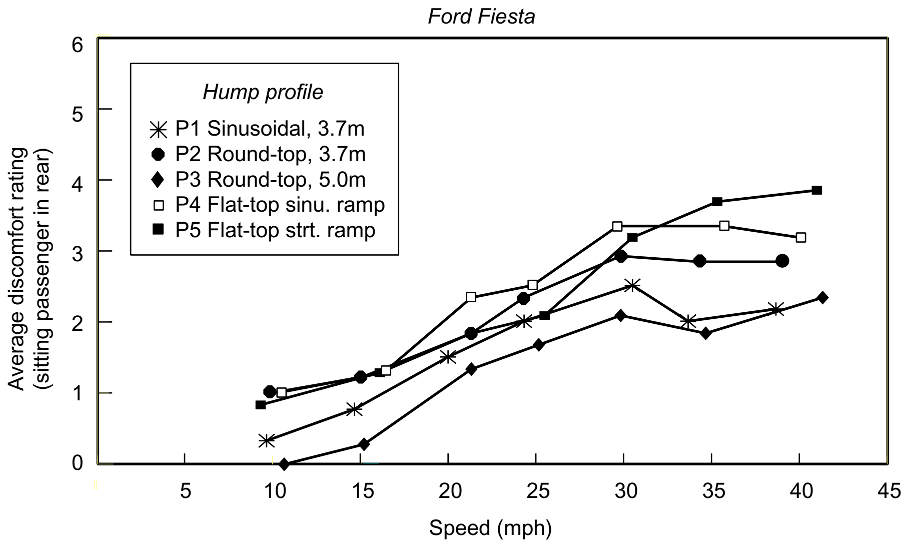
Plate 23 Dennis RS fire appliance passing over profile P5

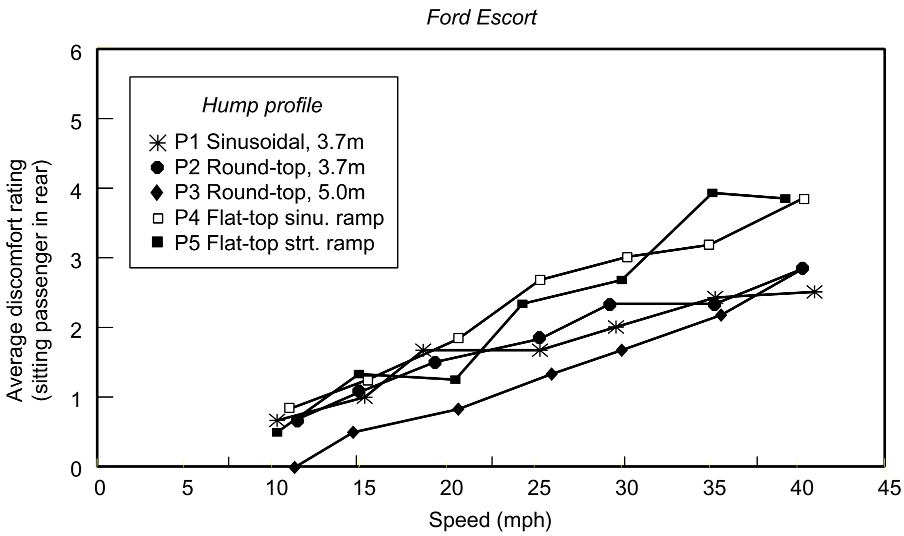
Plate 24 GMC Chevrolet ambulance (Wheel Coach conversion)

Plate 25 Ford Transit ambulance (Devon conversion)

Plate 26 Iveco Turbo daily 40–10 ambulance

Appendix C: Results for individual cars





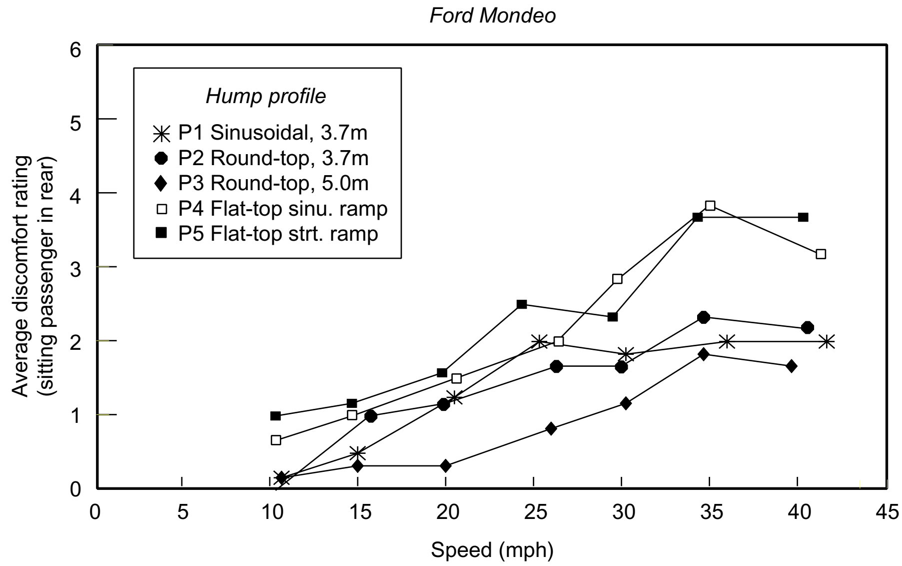


Figure C1 Average discomfort rating

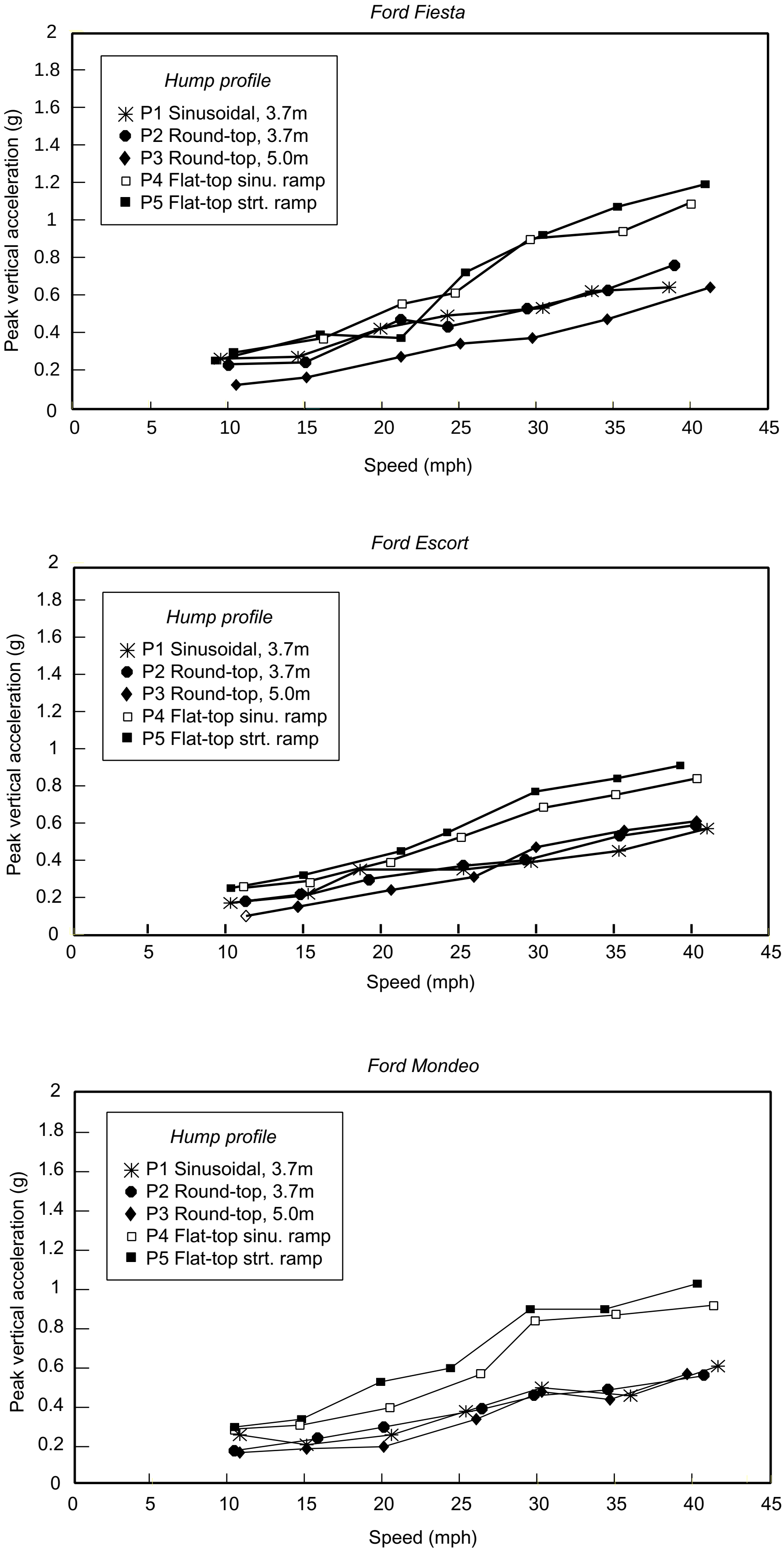


Figure C2 Peak vertical acceleration

Abstract

The original 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, than round-top or flat-top humps but little information has been available as to the degree of difference between the profiles.

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, all 75 mm high, 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 'standard' profiles were included for comparison: a 3.7m long round-top hump and an 8m long flat-top hump with straight ramps. This report gives details of the track trial at TRL and the results obtained from the measurements of passenger discomfort and vertical acceleration. A companion report, TRL Report TRL416, gives details of the results of the measurements of vehicle noise and ground-borne vibration and provides estimates of the minimum distances between hump profiles and dwellings to avoid vibration exposure.

Related publications

TRL416 *Traffic calming: Vehicle generated noise and ground-borne vibration alongside sinusoidal, round-top and flat-top humps* by G J Harris, R E Stait, P G Abbott and G R Watts. 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)

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)

PR101 *Speed at 'thumps' and low height road humps* by D C Webster. 1994 (price £25, code G)

PR32 *Speed control humps - a trial at TRL* by A R Hodge. 1993 (price £35, code H)

PR18 *Road humps for controlling vehicle speeds* by D C Webster. 1993 (price £35, code J)

Prices current at September 1999

For further details of these and all other TRL publications, telephone Publication Sales on 01344 770783 or 770784, or visit TRL on the internet at http://www.trl.co.uk.