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Traffic calming — Sinusoidal, 'H' and 'S' humps

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

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Executive Summary

The original work on speed reducing road humps was carried out in the 1970's at TRL on circular profile (round-top) humps of various dimensions. These track trials led to the adoption of the 'standard 3.7 metre long' circular profile hump which can be up to 100 mm high. Since the 1980's the regulations governing the use of road humps in Great Britain 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 and 100 mm in height and at least 900 mm long.

The Department of the Environment, Transport and the Region's Charging and Local Transport Division commissioned TRL to undertake a study of traffic calming schemes using non-standard or novel road humps. This report reviews some of the hump profiles which have been used or trialed in the Netherlands, Denmark and Great Britain. Results have been obtained for sinusoidal humps, modified round-top and sinusoidal humps, flat-top humps with sinusoidal ramps, 'H' humps and 'S' humps.

Reports from the Netherlands, Denmark and New Zealand indicated that sinusoidal humps are more comfortable for cyclists and car drivers than round-top or flat-top hump profiles, but gave little evidence as to the degree of difference in discomfort between the hump profiles. Sinusoidal humps are recommended by the Dutch traffic calming manual for use on roads with 20 kph and 30 kph speed limits. In the city of Edinburgh, sinusoidal humps (100 mm high, 3.7 m long) have been installed on residential roads and informal feedback has been positive from cyclists. Speeds of traffic measured at and between the humps were similar to those found at 75 - 100mm high flat-round-top humps.

Track trials at TRL in 1997, measuring passenger discomfort, have shown that compared with a round-top hump, a sinusoidal hump would produce a small reduction in discomfort for cyclists (both humps 75mm high and 3.7m long). The discomfort for cyclists crossing 75mm high flat-top humps was greater than that at the round-top hump and there was little difference in discomfort between flat-top humps with straight or sinusoidal ramps. Cyclists taking part in the tests indicated that the benefit gained with a sinusoidal hump was small and it was probably more important for Local Highway Authorities to ensure that there was no large upstand or discontinuity at the edge of a hump where it meets the road surface.

'Feathering' the leading edges of a round-top hump, by giving a smooth transition between the road and the hump, can have an important effect on the discomfort ratings for a given height hump. Feathering can be used to lower the discomfort caused by a hump at a given speed in the same way that a reduced gradient can be used when flat-top humps are used. Several local highway authorities in England have used flat-top humps with 'rolled over' ramps at the top to reduce the sharp angle between the ramp and plateau and give an approximate sinusoidal profile. Speed measurements indicate that the mean vehicle crossing speeds may be slightly higher than predicted for conventional flat-top humps with standard 1:10 to 1:15 ramps.

Modified sinusoidal humps have a profile that is about midway between a round-top hump and 'true' sinusoidal hump and are similar to a round-top hump with feathered leading and trailing edges. Round-top humps with feathered edges and modified sinusoidal humps (100 mm high, 9.5 m long) have been used on main roads through towns in Denmark with 50 kph (31 mph) speed limits. At schemes with the round-top humps, average speeds were reduced by about 6 mph to about 30 mph. The response from residents and road users was generally favourable but there were some complaints about levels of vibration. A 0.75m feathering was introduced to reduce the nuisance from large vehicles. A slightly smaller speed reduction of 4 mph was found during an on-road trial of modified sinusoidal humps.

Track trials at TRL in 1992, indicated that 100 mm high, 10 metre long round-top humps with feathered leading and trailing edges were not suitable for use on 40 mph speed limit roads because of the likelihood of buses grounding at speeds of 30 mph or more. Experience from Denmark, referred to above, suggests that such humps might be suitable for controlling speeds on 30 mph limit roads but other measures, such as speed cushions which reduce the discomfort experienced by occupants of buses and large commercial vehicles, may be a better option.

The principle of the 'H' or 'combi' hump was developed in Denmark as a result of trials which showed that it was possible to design a combined car and bus hump with two longer shallower outer profiles to take the tyres of buses and with a shorter inner profile to take cars. The dimensions of the profiles could be chosen so that the car and bus speeds across the hump were comparable.

In 1996, Fife Council carried out an off-road trial of 'H' and 'S' humps with a variety of vehicles including cars, buses, lorries and commercial vehicles. The objective of the trials was to design and test 'H' and 'S' humps suitable for bus and car use which would maintain speeds at 30 mph. The 'S' hump was developed by Fife Council in order to solve anticipated problems with drainage, construction and operational difficulties relating to the angular design of the 'H' hump. It works on a similar principle to 'H' humps but has a gradually varying ramp gradient across each lane rather than a marked lip between the car and bus ramps. The trials were considered successful with some minor modifications to ramp design and gradient for on-road use.

In 1997, Fife Council installed a traffic calming scheme on South Park Road, Glenrothes, consisting of 3 'H' humps and 4 'S' humps. The construction costs were £2000 for an 'S' hump and £2500 for a 'H' hump. The 85th percentile speeds between the humps were reduced by about 7 mph to about 29.5 mph. The speeds at the 'H' humps were similar to those at the 'S' humps, with bus speeds about 5 to 6 mph lower than car speeds. On

average, the mean speed of cars (about 22 mph) and buses (about 16.5 mph) are about 6 mph higher than the speeds of cars and buses over 75mm high humps. Video analysis indicated that few drivers (less than 0.5%) minimised their discomfort by driving down the centre of the road. Average daily vehicle flows were reduced from 9000 to 6000 vehicles per day (-33%).

In 1998, Northamptonshire County Council replaced a pair of 1880mm wide cushions with a ‘S’ hump in Northampton. The effect of changing from the 1880mm wide cushions to the ‘S’ hump was that the mean speed of cars was increased marginally by about 1.5 mph to 19 mph and the mean speed of buses was reduced by about 2.5 mph to about 16.5 mph. While the mean bus speed at the ‘S’ hump in Northampton was similar to that at the ‘S’ humps in Fife, the mean speed of cars at the ‘S’ hump in Northampton was lower than that in Fife.

The ‘S’ hump, as with most traffic calming measures, does not offer a complete solution in terms of speed reduction. Initial results indicate that ‘S’ humps appear to allow higher operating speeds for large buses than 75mm high humps, but lower operating speeds than cushions. Mean speeds of cars at the ‘S’ humps are similar to those at narrow width (1600mm) cushions thus, like narrow cushions, ‘S’ humps may not provide sufficient speed reduction in 20 mph zones without additional measures. ‘S’ humps could be usefully installed within a speed cushion scheme, where raised junctions or pedestrian crossing are required.

1 Introduction

Vertical deflections (road humps) were developed by TRL for the Department of Transport (DOT), now the Department of Environment Transport and the Regions (DETR). Trials were carried out on the test track at TRL using humps of various heights and profiles (Watts, 1973). 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 and Clement, 1982).

The original Highways (Road Hump) Regulations (DOT, 1983 & 1986) allowed round-top humps, 3.7 m in length with heights of 100 mm (1983) and 75 mm to 100 mm (1986), 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).

The current Hump Regulations (DOT, 1996) and those for Scotland (Scottish Office, 1984 and 1998) 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 and with no vertical face greater than 6 mm. It should be noted that road markings for some humps and the use of humps where the height could be varied mechanically still require special authorisation.

Since 1990, when lower humps and flat-topped humps were allowed, traffic calming has become more widespread in Great Britain. Humps are an important tool for Highway Authorities because they are effective at controlling speeds, and are generally applicable to most road layouts. 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).

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 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 (DOT, 1998; Layfield and Parry, 1998) which generally cause less discomfort at a given speed or may be traded for 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 (sometimes called the bell shape hump) have been used in the Netherlands, Denmark and Scotland (see Figure 2). These humps are similar to a round-top hump but have a shallower initial rise. Further work in Denmark has lead to the development of a modified sinusoidal profile (Lahrmann and Mathiasen, 1992).

Round-top humps with a longer cross-section in the direction of travel provide less discomfort at higher speeds

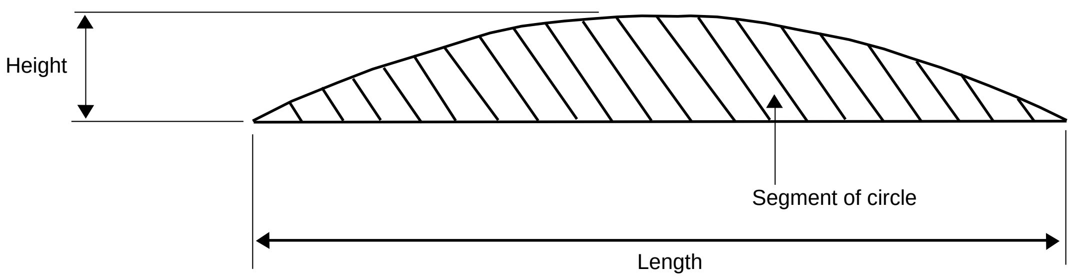


Figure 1 Diagram of a typical cross section of a round-top hump

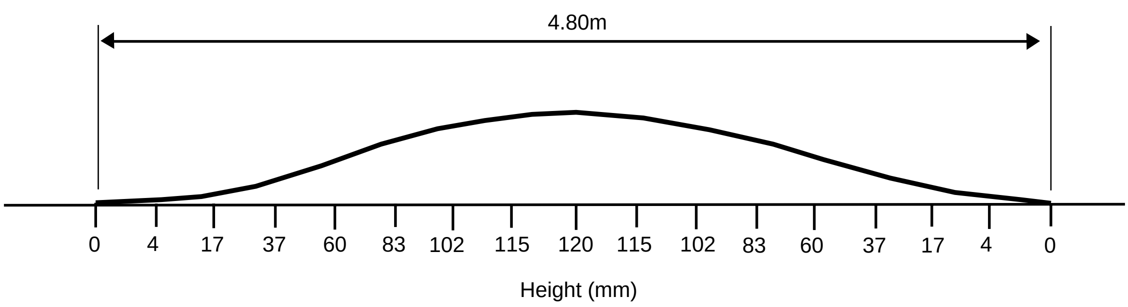


Figure 2 Diagram of a typical cross section of a Dutch sinusoidal hump

and have been used in Denmark as speed controlling devices allowing higher speeds than the standard 3.7 m round-top hump. Some of these round-top profiles have been modified by feathering the leading and trailing edges of the hump to reduce the initial rise (Herrstedt et al, 1993). Trials of long round-top humps and round-top humps with feathered leading and trailing edges for use on 40 mph speed limit roads were carried out by Hampshire County Council and TRL in 1991 and 1992 (Hodge, 1992; Hodge, 1993). These were deemed to be not suitable for use in England and Wales because of grounding problems with buses during the TRL track trials.

A novel 'combi-hump' which is a combination of a hump profile suitable for cars and a longer profile suitable for buses and commercial vehicles, was first reported by Kjemtrup, 1990. It has now been called an 'H' hump because the plan view of the hump resembles a letter 'H'. A number of 'H' humps have been installed in Denmark and in Scotland (see Section 3). The 'S' hump was developed by Fife Council (Fife Council, 1996) to overcome some of the deficiencies of the 'H' hump. It works on a similar principle to 'H' humps but has a continuous curve rather than a marked lip between the car and bus ramps and avoids the need for additional drainage gullies.

In order to improve the advice available to local highway authorities, the Charging and Local Transport Division (CLT) of DETR commissioned TRL to undertake a review of some of these novel vertical deflections. The results of the study are given in this report. Section 2 describes the use of sinusoidal humps in the Netherlands, Denmark and Scotland (Edinburgh), and round-top humps with feathered leading and trailing edges. Section 3 describes the use of 'H' and 'S' humps including the results of off-road and on-road trials carried out to determine the safety and speed reduction likely to be achieved on the Public Highway.

2 Sinusoidal humps

2.1 Sinusoidal humps in the Netherlands

The sinusoidal hump profile (see Figure 2) was based on a study by Delft Technical University using field experiments and a computer model that simulated the behaviour of a car and driver. The results indicated that traffic humps for 85th percentile crossing speeds of 30 kph must be 4 - 5 metres long and that the sinusoidal hump profile was the most preferable of those tested (De Wit and Slop, 1984, De Wit, 1993).

Sinusoidal humps have been used in Dutch 30 kph zones and are the recommended road hump profile (height 120 mm, length 4.5 to 5 m) for use on cycle routes because they are less 'annoying' for cyclists than the round-top or flat-top profiles (Lines and Castelijn, 1991 - translation of Dutch 30 kph zone design manual, 1984).

Information on the effect on speed of the 120 mm high, 4.8 m long sinusoidal humps was gathered in the city of Enschede (De Wit and Slop, 1984). Mean and 85th percentile speeds *at* the humps were reduced by 11 and 15 kph (7 and 9 mph) respectively to 20 and 26 kph (12 and 16 mph).

Haus-Klau et al (1992) report that sinusoidal hump profiles have been further developed in the Netherlands and that the 1988 Dutch traffic calming manual gives details of hump profiles for roads with 20, 30 and 50 kph speed limits. Sinusoidal humps are recommended for use on roads with 20 kph (height 120 mm, length 3.36 m) and 30 kph speed limits (height 120 mm, length 4.80 m). Flat-top humps (height 120 mm, plateau length 2.4 m, overall length 12 m) are recommended for roads with a 50 kph limit.

In the UK, the Road Hump Regulations (DOT, 1996) allow a maximum hump height of 100 mm. Experience with round-top humps indicates that sinusoidal hump heights of greater than 100 mm would cause grounding problems for cars with long wheelbases and low ground clearances (eg limousines and hearses) when crossing humps of 3.7 m or less in length (Webster, 1993b).

2.2 Sinusoidal humps in Denmark

The Danish guidelines for speed reducing measures in urban traffic areas show a wide variety of different road hump profiles: round-top, dome-shaped and flat-top (Danish Road Directorate, 1991). For round-top and dome-shaped humps, the recommended height is 100 mm and the length is 3.0 m, 4.0 m, 6.5 m and 9.5 m for use on roads where the desired speeds are 20 kph, 30 kph, 40 kph and 50 kph respectively.

Sinusoidal humps have also been tried in Denmark with the aim of reducing the jolt to passengers at the beginning of the hump (Lahrmann and Mathiasen, 1992). A series of three 4.0 m long, 100 mm high sinusoidal humps were constructed in asphalt on a private road at Kronen near Aalborg where the desired speed was 30 kph. The humps were spaced at 70 metres apart. Measurements of the hump profile showed that the constructed profile was about 5 mm lower than the specified profile.

Speed measurements taken mid-way *between* the humps showed that the proportion of vehicles travelling at more than 30 kph (19 mph) had fallen from 52% to 15% and the proportion above 40 kph (25 mph) had fallen from 13% to 1%. Cyclists could pass over the humps without inconvenience and noise and vibration were not thought to be a problem.

In test drives, it was found that there was no jolt at the beginning of the hump and at a sufficiently low speed (<20 kph), the humps could be passed over by a car without discomfort. At 30 to 35 kph the humps were very unpleasant to pass over. Interviews with local residents indicated that the humps were somewhat severe and caused discomfort below the desired speed of 30 kph (19 mph).

As a result of the experience with the 4 m sinusoidal humps in Kronen, a modified 4 m sinusoidal profile was developed and tried on different roads in Vejle and Silkeborg. The profile used was midway between the circular (round-top) and sinusoidal profiles (see Section 2.4 and Appendix A). The authors reported that experiences with the modified humps have been good and that they appear to suit a desired speed of 30 kph.

2.3 Sinusoidal humps in New Zealand

Sinusoidal humps have also been used in New Zealand where it was reported (Moses, 1992) that 'the crossing of the hump whilst causing a significant reduction in speed appeared to be more comfortable than the 'Watts' profile round-top hump'.

2.4 Sinusoidal humps in Scotland

The City of Edinburgh Council installed thirty-five sinusoidal humps (100 mm high and 3.7 m long) on residential roads in the Grange area of Edinburgh in 1995 (see Figures 3 and 4). The aim was to reduce the high vehicle speeds along the roads. The Grange area has a relatively high cycle use (about 5% of journeys to work by pedal cycle) and Edinburgh Council were keen to use sinusoidal humps because they were thought to be more cycle-friendly than other road hump profiles (see Section 2.1). There were no bus routes using the roads where the humps were installed.

The humps were constructed with asphalt to the profile shown in Figure 5 and no problems with hump construction were reported by the local authority. The cost for each sinusoidal hump was similar to a round-top hump (of the same 100 mm height).

Edinburgh have measured changes in vehicle speeds and flows but have not had any formal feedback from the residents, cyclists or emergency services. Informal feedback has been positive particularly from cyclists and it is likely that sinusoidal humps will be considered for future schemes.

2.4.1 Changes in vehicle speeds

Edinburgh Council measured 'before' speeds on Fountainhall Road (and on the parallel roads). The results showed that 64% of vehicles exceeded 30 mph and 11% exceeded 40 mph. The mean and 85th percentile speeds were about 33 mph and 39 mph respectively. These speeds were similar on all of the parallel roads and are typical for a relatively wide road (about 8 metres) with few parked cars. 'After' speeds were measured *at* a hump on Fountainhall Road and mid-way *between* the humps on Relugas Road, St Albans Road and West Relugas Road.

The results given in Table 1 show that the mean speeds were reduced from about 33 mph to 15.5 mph *at* a hump and to 21 mph - 25 mph mid-way *between* the humps at hump spacings ranging from 70 to 132 metres. These results are similar to those obtained for 75 - 100 mm high round-top humps and 75 - 100 mm high flat-top humps with ramp gradients of 1:10 to 1:15 (Webster and Layfield, 1996).

Table 1 Vehicle speeds (mph) in Grange area, Edinburgh

	Before		*After*		*Difference*		*Hump spacing*
Location	*Mean*	*85%*	*Mean*	*85%*	*Mean*	*85%*	*metres*
At hump							
Fountainhall Road	33	39	15.5	20	17.5	19	-
Between humps							
Relugas Road	33	39	21.1	24	11.9	15	70
St. Albans Road	33	39	21.9	25	11.1	14	100
West Relugas Road	33	39	24.5	28	8.5	11	132

2.4.2 Changes in vehicle flows

Edinburgh Council measured the 'before' and 'after' vehicle flows on Grange Terrace/ Fountainhall Road and West Relugas/Relugas Road in the peak times between 8.00 to 9.00 am and 16.30 to 17.30 pm. The vehicle flows on these roads were generally low; the 'before' peak period two-way flows varied between about 90 and 430 vehicles/hour. The 'after' flows varied between about 65 and 315 vehicles/ hour. The vehicle flows were reduced by between 17% and 33% with an average of 23%. The fact that the before flows were taken 9 years previously in 1988 was not thought by the Council to be significant as the area has not changed greatly during the intervening period. These results agree with previous studies that indicate that installing road humps encourages traffic onto alternative routes.

2.4.3 Changes in injury accidents

There has been a small reduction (not statistically significant) in injury accident frequency. In the 3 year period before the sinusoidal humps were installed, there were two slight injury accidents (0.67 accidents/year) which were both at junctions. In the 23 months since the installation there has been one slight injury accident (0.52 accidents/year) which involved a car and a cyclist at a junction.

The effect of sinusoidal humps on vehicle speeds is similar to that of round-top and flat-top humps and it is likely that, on average, the effect on accidents (about 60% reduction for 75 to 100 mm high humps) will also be similar. However more sites with sinusoidal humps would be needed to confirm this result.

2.5 Modified round-top and modified sinusoidal humps

2.5.1 Round-top humps with feathered ramps

The initial jolt experienced when crossing a round-top hump can be lessened by 'feathering' the leading and trailing edges to give a smooth transition between the road and the hump. The subsequent hump profile is about midway between a round-top and a 'true' sinusoidal profile.

The London Borough of Richmond modified existing round-top humps (75 mm high and 3.7 m long) on Amyand Park Road in 1995 by digging out the leading edges of the humps and reprofiling the hump to give a more gentle initial slope. These modified humps have been used to assist cyclists while still maintaining the low vehicle speeds already achieved. Speed measurements have not been taken since the modifications, but the humps are reported by the Borough to be working satisfactorily.

Trials were carried out by Hampshire County Council (Hodge, 1992) using various hump profiles which were intended to be used on 40 mph roads. These included an eight metre long, 100 mm high round-top hump and two similar humps, one with a 0.5 metre feathering at each end (9 m overall length, see Figure 6a) and another with a one metre feathering (10 m overall length, see Figure 6b). A Ford Fiesta was used in the trials and the discomfort rating scale and the results are given in Tables 2 and 3 respectively.

The results in Table 3 show that feathering the leading edge of a round-top hump can reduce the discomfort ratings. Feathering can therefore be used to lower the discomfort

Figure 3 Example of a sinusoidal hump on South Lauder Road, Edinburgh

Figure 4 Sinusoidal hump on South Lauder Road, Edinburgh (looking north)

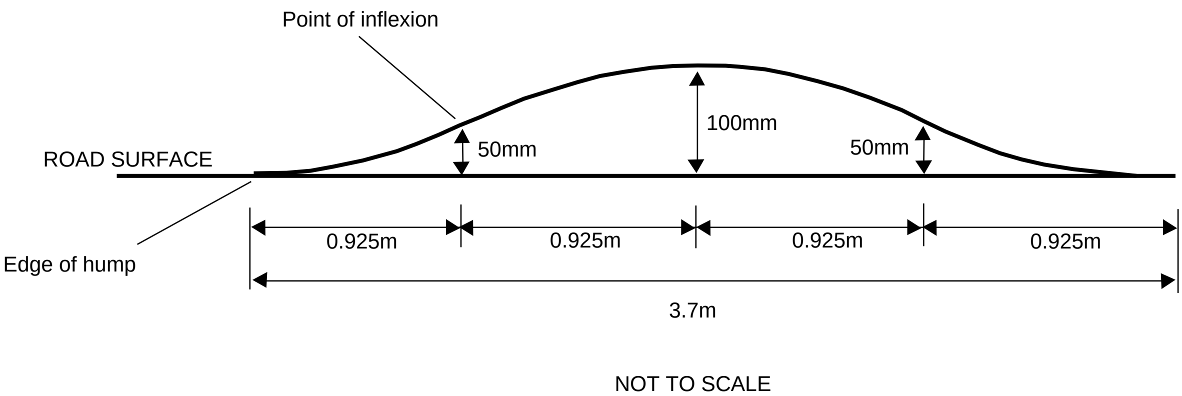


Figure 5 Diagram of sinusoidal hump in Edinburgh

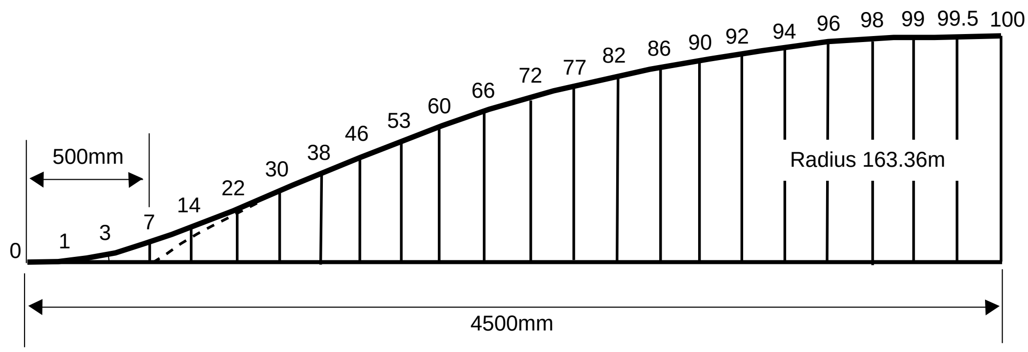


Figure 6a Round-top hump with 0.5 metre feathering

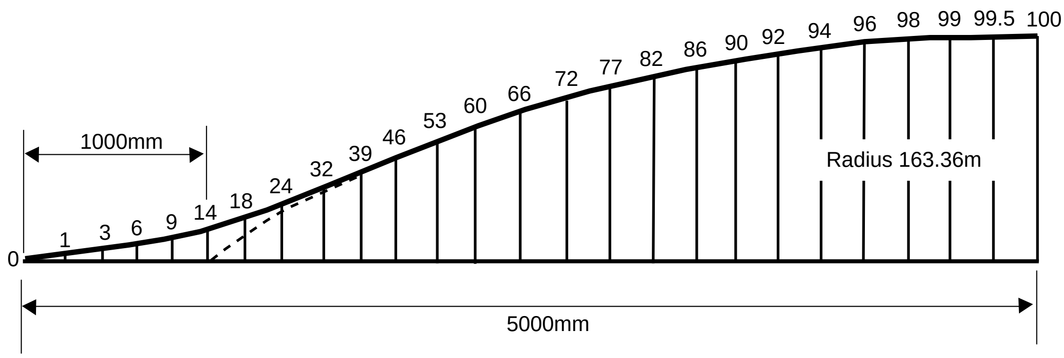


Figure 6b Round-top hump with 1.0 metre feathering

Table 2 Rating system for discomfort when passing over road humps

Discomfort rating	*Discomfort description*
0	Comfortable
1	
2	Slightly uncomfortable
3	
4	Uncomfortable
5	
6	Very uncomfortable

Table 3 Effect of feathering the ramps of a 100 mm high round-top hump

Hump description	*Total length (metres)*	*Speed (mph)*	*Discom-fort rating*	*Speed (mph)*	*Discom-fort rating*
3.7 m long	3.7	20	3.5	30	5.3
8.0 m long	8.0	20	1.1	30	2.0
8.0 m (0.5 m feathering)	9.0	20	0	30	1.3
8.0 m (1.0 m feathering)	10.0	20	0	30	0.3
8.0 m (1:12.5 ramps)[1]	10.5	20	0.8	30	1.8
8.0 m (1:20 ramps)[1]	12.0	20	0.7	30	0.8

[1]*Flat-top humps (8 m plateau)*

caused by a round-top hump at a given speed in the same way that a reduced gradient can be used for flat-top humps. At 30 mph, changing from a 1:12.5 to a 1:20 gradient lowered the discomfort 1 point on the discomfort rating scale. This is similar to the reduction in discomfort achieved with a feathering of 0.5 m to 1.0 m. It has been estimated from (Webster and Layfield, 1996) that reducing the ramp gradient of flat-top humps from 1:10 - 1:15 to 1:15 - 1:20 might increase crossing speeds by about 5 mph.

It was reported that the effectiveness of the modified humps seemed to be due to the effect on the vehicle leaving the hump which caused large suspension movements. The main restraining effect on speed was the likelihood of causing damage to the vehicle rather than passenger discomfort.

Further trials at TRL, with a wider range of vehicles, indicated that the 8 m round-top hump with 1 m feathered edges and the 8 m flat-top hump with 1:12.5 ramps were not suitable for use on 40 mph speed limit roads. For both humps, buses had grounding problems at 30 and 40 mph because of the heavy pitching motion. For the feathered hump in particular, the occupants of cars travelling at high speeds did not appear to suffer much discomfort, leading to concerns about the risk of high speed loss of control. A motor cycle rider was observed to experience difficulty in controlling the machine at 50 mph on the feathered hump (Hodge, 1993).

Round-top humps (100 mm high, 9.5 m long) have been used in Denmark to reduce speeds on roads through towns with a 50 kph (31 mph) speed limit. Research in Denmark at 14 sites in Frederiksborg County has shown that round-top humps of this type reduced speeds by about 9 kph (6 mph) to an average of 48 kph (30 mph). There were between 2 and 9 humps on each section of road. At Endrup, the percentage of drivers exceeding 50 kph (31 mph) has been reduced from 82 per cent to 37 per cent. The speed reduction has brought about an overall reduction of 50 per cent in accidents and the reported accidents have been less serious (Jensen, 1995).

Although the feedback from the public was generally good, there were complaints of vibrations in properties near the humps and criticisms from the bus companies about the design of the round-top hump. Jensen reported that buses and lorries were expected to cross at a speed about 15 kph (9 mph) lower than cars, but Jensen noted that there was no specific warning for the drivers of these vehicles. A 0.75 m feathering has been incorporated (see Figure 7) to minimise the 'nuisance' from large vehicles.

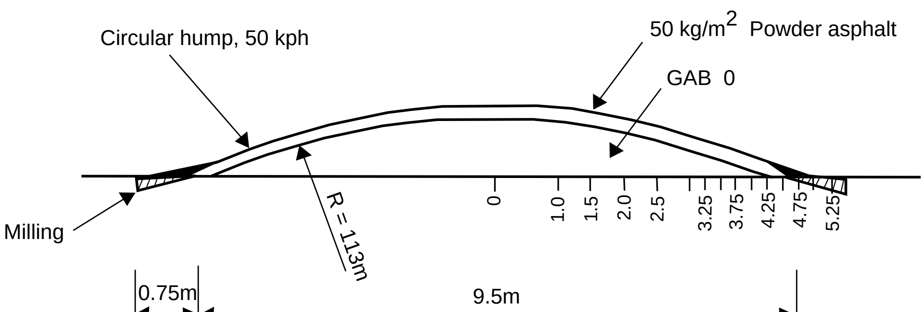
2.5.2 Modified sinusoidal humps

Modified sinusoidal hump profiles have also been used in Denmark (Lahrmann and Mathiasen, 1992). The hump profile is such that the initial vertical displacement is approximately twice that of a sinusoidal hump but is still about half that of a round-top hump. These humps are very similar to the modified round-top humps with feathered ramps discussed in the previous Section. A comparison of the hump profile dimensions are given in Table 4 and Figure 8.

The sinusoidal hump example given in Table 4 is for a 9.5 metres long hump; dimensions were also given by the authors for 4.0 metres and 6.5 metres long humps for use on roads with lower speed limits of 30 and 40 kph respectively (see Appendix A).

Two modified sinusoidal humps, 9.5 metres long and 100 mm high were constructed on an access road in Snejbjerg, Denmark at a spacing of 210 metres (Lahrmann and Mathiasen, 1992). The average car speeds mid-way *between* the humps were reduced by 6 kph (4 mph) to 44 kph (27 mph) and bus/lorry speeds were about 15 kph (9 mph) lower (Herrstedt et al, 1993). A bus route crosses one of the humps and it is reported that it is acceptable to the bus driver and bus passengers. The cost of each hump was DKK 20,000 (about £1800) which can be compared with a cost of about DKK 15000 (about £1350) for a round-top hump or DKK 75,000 (about £6800) for an 'H' hump.

Modified sinusoidal humps (100 mm high and 9.5 m long) have also been used on main roads at 10 towns in Nordjylland County in Denmark. It has been reported (Jakobsen, 1994) that the modified sinusoidal humps showed reduced average speeds from over 60 kph (37 mph) to under 50 kph (31 mph). After the humps were installed, it was the fastest drivers who reduced their speeds and few drivers exceeded the 50 kph speed limit by



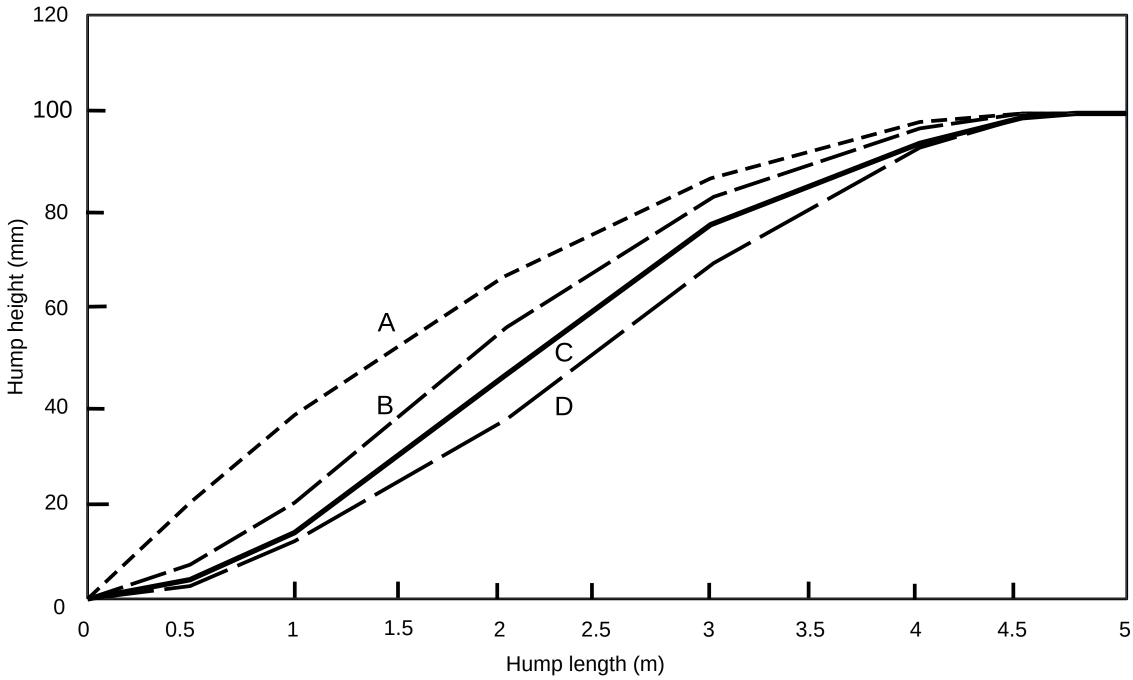
Length (m)	0	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.25	4.5	4.75
Height (cm)	10	9.5	9.0	8.3	7.3	6.0	4.5	3.0	2.3	1.5	1.0

Figure 7 Round-top hump with 0.75 metre feathering (Jensen, 1995)

Table 4 Comparisons of dimensions of standard and modified road hump profiles

Horizontal distance along road (mm)	*Danish hump profiles (9.5 m long)* Round-top standard	Sinusoidal modified	Sinusoidal standard	*Feathered round-top humps in HCC and TRL trials* Round-top[1] 0.5 m feather	Round-top[2] 1.0 m feather
	Height of hump (mm) at given distance along road				
0	0	0	0	0	0
500	20	7	3	7	4
1000	38	20	11	26	14
2000	67	56	37	63	46
3000	87	83	69	88	77
4000	98	97	93	99	94
4500	100	100	99	100	99
4750	100	100	100	-	100
5000	-	-	-	-	100

[1] 500 mm feathering to give a 9 metres long hump
[2] 1000 mm feathering to give a 10 metres long hump



A = Danish standard round-top, B = Danish modified sinusoidal
C = TRL 40 mph hump (1.0 metre feathering)
D = Danish standard sinusoidal

Figure 8 Comparison of various hump profiles

more than 10 kph. The modified sinusoidal humps were perceived by road users as ‘very soft’ because they can be crossed at speeds greater than 50 kph without the feeling that the car might be damaged.

The humps were constructed in asphalt and there were initial problems in achieving the correct profile for the humps. The Nordjylland County Highway Authority now accepts humps with a maximum deviation of +/- 10 mm from the specifications at the top of the hump ie 90 - 110 mm. However, the shape of the hump has to be maintained so that any deviation is distributed along the length of the hump.

A questionnaire study in Egense, one of the towns with the modified sinusoidal humps, showed that the humps were thought to be effective in reducing speeds, and at improving road safety for cyclists and pedestrians. Car drivers also approved of the humps, for use in smaller towns, particularly compared with other hump designs.

There have been complaints from some residents about noise and vibration. Overall noise levels were about the same as before the humps were installed but some short duration, loud noise has been detected. Where previously there was a constant traffic noise, there are now variations in the noise level caused by braking and acceleration. The most disturbing noise was caused by lorries with trailers crossing the humps. Vibration measurements were carried out in one house where the inhabitant had complained but the maximum vibrations were so small that they could not cause damage to buildings.

The results from this study have encouraged the County Highway Authority to consider the use of modified sinusoidal humps as speed reducing measures on main roads at many other towns in the Nordjylland County.

2.6 Flat-top humps with sinusoidal ramps

Flat-top humps with preformed sinusoidal ramps (75 mm high) have been used in 20 mph zones in Daneshouse, Burnley and Fairfield renewal area in Warrington, but as yet no detailed information on the speed reductions obtained is available.

Flat-top humps (75 mm high) which have ramps and plateau made in blockwork, are often ‘rolled over’ at the top to reduce the sharp angle between the ramp and plateau and give an approximate sinusoidal profile. Norfolk County Council have several schemes containing humps of various overall lengths but they are generally in the range 4 to 6 metres with 1:13 or 1:15 ramp gradients. Speed measurements taken by Norfolk have shown that the mean vehicle crossing speeds are about 16 to 18 mph for cars, with corresponding *between* hump speeds being approximately 22 mph for hump spacings of 70 - 80 metres. These results are slightly higher than predicted for conventional flat-top humps with 1:10 to 1:15 ramps (13 mph *at* and 20 mph *between* humps, Webster and Layfield, 1996). Warwickshire County Council have also successfully used a similar profile in the Rugby 20 mph zone. The humps used were 75 mm high with nominal 1:15 ramps and speed measurements showed that the ‘average’ *at*/*between* hump speeds were 18 mph.

2.7 TRL track trial of sinusoidal humps

Track trials at TRL in October 1997, measuring passenger discomfort, have shown that compared with a round-top hump, a sinusoidal hump would produce a small reduction in discomfort for cyclists (both humps 75mm high and 3.7m long). The discomfort for cyclists crossing 75mm high flat-top humps was greater than that at the round-top hump and there was little difference in discomfort between flat-top humps with straight or sinusoidal ramps. There was little, if any, benefit in terms of passenger discomfort for car or bus passengers in using a sinusoidal hump in preference to a round-top hump or in using sinusoidal ramps in preference to straight ramps.

Cyclists taking part in the tests indicated that the benefit gained with a sinusoidal hump was small and it was probably more important for Local Highway Authorities to ensure that there was no large upstand or discontinuity at the edge of a hump where it meets the road surface.

2.8 Continuous vertical deflections (waves)

It has been proposed by an Australian researcher (Hidas, 1993) that continuous vertical deflections (waves) could be used for controlling vehicle speeds and that test sites with various wave profiles should be built. The author discusses the advantages and disadvantages of such a scheme but raises issues of driver behaviour and safety.

An example of waves or undulations has been tried in England (Windle and Hodge, 1993) but was removed after an accident in which a caravanette negotiating the undulations went out of control and overturned. A series of four 80 mm high undulations were constructed in the New Forest by Hampshire County Council to control speeds on a 40 mph speed limit road. Monitoring of the site had suggested that although some drivers crossed the undulations safely at 55 mph others found 30 mph uncomfortable, so maximum speed 30 mph warning signs were added (Alexander, 1990).

3 ‘H’ and ‘S’ humps

The principle of the ‘H’ or ‘combi’ hump was developed in Denmark as a result of trials with a single decker bus (Leyland) and a medium-sized car (VW Golf) passing over a range of round-top hump profiles (Kjemtrup, 1990). These tests showed that it was possible to design a combined car and bus hump for a reference speed of 30 kph (19 mph) with two longer shallower outer profiles (8 m long, 600 mm wide set about 1500 to 1650 mm apart) to take buses and with a steeper inner profile (4 m long, 1500 mm wide) to take cars. The dimensions of the profiles were chosen so that the car and bus speeds across the hump were comparable. In order to secure the safety of motorcyclists, it was recommended that the difference in height between the bus and car profiles should be a maximum of 50 mm and levelled up with asphalt to give a 1 in 2 gradient.

Like the speed cushion, the ‘H’ hump (Figure 9) aims to reduce the discomfort to occupants of buses and large commercial vehicles. With a speed cushion, the inner rear wheels of twin rear wheeled vehicles may cross over the edges of the cushion and cause some discomfort. This does not happen with the ‘H’ hump but there is some concern that the inner wheels may not be supported when traversing the ‘H’ humps outer ramps.

The ‘S’ hump was developed by Fife Council (Fife Council, 1996) in order to solve anticipated problems with drainage, construction and operational difficulties relating to the angular design of the ‘H’ hump. The ‘S’ hump is similar in principle to the ‘H’ hump with shallower ramps for buses and large commercial vehicles, and steeper ramps for cars. For ‘S’ humps, this has been achieved by imposing a sinusoidal curve (in plan view) on the front and back edges of the speed table plateau.

3.1 ‘H’ humps in Denmark

An ‘H’ hump was installed in the Danish town of Herning with ‘very satisfactory’ results (Kjemtrup, 1990). Two further ‘H’ humps were installed in Aalborg (Herrstedt et al, 1993) which had single lane operation over the hump and a cycle lane bypass along each side. The humps were marked by 30 kph signs and their presence was enhanced with bollards. The cost of each hump was DKK 75,000 (£6,800).

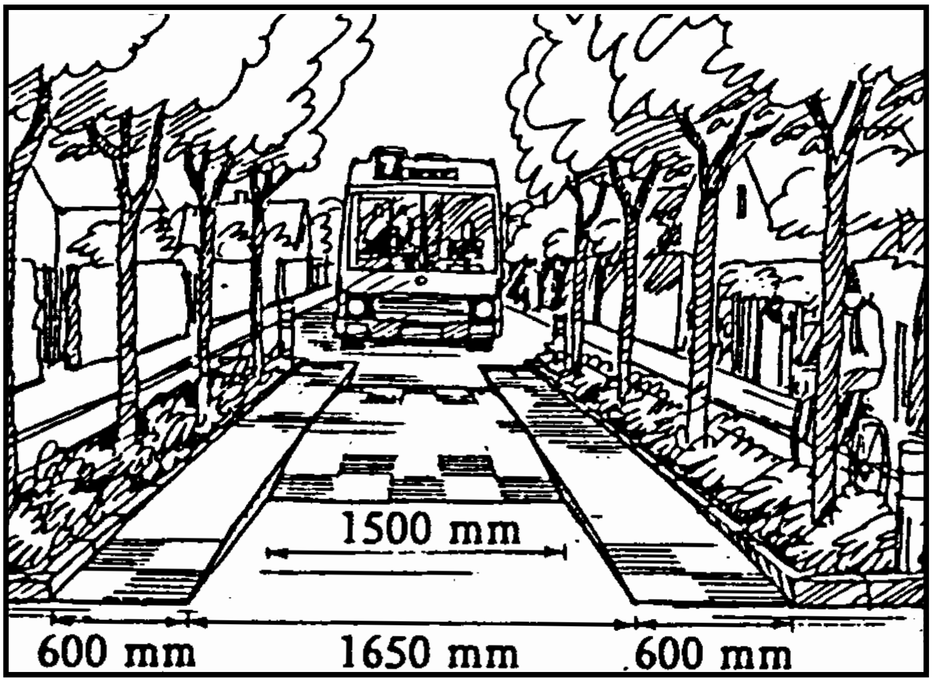


Figure 9 Example of an 'H' hump designed by Kjemtrup

At the hump in Aalborg, the mean crossing speeds for cars and heavy vehicles were 25 kph (16 mph) and 20 kph (12 mph) respectively. The 85th percentile speeds were 30 kph (19 mph) and 25 kph (16 mph) respectively. The humps were acceptable to both bus drivers and passengers. Most car drivers put one wheel on the bus profile but this did not change the speed reducing effect. 'H' humps are normally used in conjunction with narrowing to one lane but they can be used as 2-lane speed reducers where the carriageway is at least 6 metres. (Danish Road Directorate, 1991; Herrstedt et al, 1993).

3.2 'H' and 'S' humps in Scotland and England

3.2.1 'H' hump trials in Strathclyde

Strathclyde Regional Council and Strathclyde Passenger Transport Executive carried out an off-road trial in 1992 of various hump profiles, including an 'H' hump, with a wide range of vehicles. The 'H' hump tested was 80 mm high with outer 1:25 ramps for buses set 1450 mm apart and an inner 1:7.5 ramp for cars (Strathclyde, 1993). The main purpose of the tests was to find dimensions which would allow buses to use the outer shallower ramps which would be too wide for cars. This can be more difficult in Britain because of the different bus designs, many of which have twin rear wheels. This means that the inner wheels may hang over the edge of the outer ramps.

The tests were carried out at low speeds and measurement of the bus rear axles showed that almost all the buses with the exception of one of the mini-buses could get at least the whole of the outer tyre of the twin rear wheels on the outer shallower ramps. No adverse effects were noticed on any of the buses and all operators were happy with the performance of the buses. The bus drivers estimated that on the road they would need to slow down to 15 mph to line the buses up to pass over the shallower ramps.

The results from the trials were encouraging and an 'H' hump scheme was proposed by Strathclyde for New Road, Ayr. This consists of a single 'H' hump on a road used mainly by buses where the hump would be used to deter car drivers from using the road as a short cut. At the present time, implementation of the scheme has been postponed due to lack of funding.

3.2.2 'H' and 'S' hump trials in Fife

Trials of the 'H' and 'S' hump were carried out by Fife Council in 1996. The objective of the trials was to design and test 'H' type humps suitable for bus and car use which would maintain speeds at 30 mph (*eg* on district distributor roads), (Fife Council, 1996).

The 'H' hump used in the Fife trials was 75 mm high with shallow (1 in 24) outer ramps (700 mm wide) set 2000 mm apart and a steeper (1 in 12) inner ramp with a width of 1400 mm at the bottom and 2000 mm at the top. The transition between the outer shallow ramps and the inner steep ramp was constructed with a gradient of 1 in 8.

The 'S' hump used in the trials was 75 mm high with a minimum gradient of 1 in 30 for the outer shallower ramps used by large vehicles and a maximum gradient of 1 in 11 for the steeper inner ramp used by cars.

The durability of the humps could not be assessed at the trial but it was noted that, because of additional kerbing and the gully, the 'H' hump might not be as durable as the 'S' hump which was expected to be as durable as a conventional round-top hump.

A variety of vehicles (including cars, buses, lorries and emergency service vehicles) were driven over the humps at a range of speeds and passenger discomfort was assessed by passengers using the same 6 level discomfort rating scale given earlier in Section 2.5.1. A summary of the results of the trials for the 'H' and 'S' humps are given in Table 5.

Table 5 Summary of discomfort levels for 'H' and 'S' humps (Fife trials)

Speed (mph)	*'H' hump*			*'S' hump*		
	Cars	*Buses*	*Lorries*	*Cars*	*Buses*	*Lorries*
10	0.6	0.2	0.5	0.3	0.4	0.5
15	1.1	0.9	1.8	0.6	1.0	2.2
20	2.2	1.9	3.0	1.4	2.1	3.8
25	3.3	2.7	4.1	2.5	2.8	4.9
30	4.1	3.4	4.7[1]	3.3	3.4	5.6[1]
Average (10-30 mph)	2.3	1.8	2.8	1.6	1.9	3.4

[1]*Estimated values (not all lorries tested at 30 mph)*

The average discomfort levels for the buses tested were very similar on the 'H' and 'S' humps and were acceptable to drivers and passengers at 25 mph. For the 'H' hump, the average passenger discomfort levels for the cars tested were slightly higher than for the buses tested. At 30 mph the average discomfort rating on the 'H' hump for cars was 4.1. This was considered sufficient to maintain an 85th percentile speed of 30 mph. For the 'S' hump, the average passenger discomfort levels for the cars tested were slightly lower than for the buses tested. At 30 mph the average discomfort rating on the 'S' hump for cars was 3.3. This was not considered sufficient to maintain an 85th percentile speed of 30 mph.

A one point reduction in the level of discomfort was experienced when cars were driven off-centre with one wheel on the shallow ramp. It was thought that this might lead to some cars being driven towards the centre on the carriageway to use the offside shallow ramp and reduce discomfort to the drivers.

The average discomfort levels for the lorries tested was higher than for the cars and buses and it was thought likely that the humps would be effective at maintaining lorry speeds at about 20 to 25 mph. The snow plough coped adequately with the 'H' and 'S' humps but it was noted that the 'H' hump might suffer from retention of snow on the central ramp area. It was also thought that the durability of the 'H' and 'S' humps might be affected by snow clearing operations but it should be no worse than the damage currently experienced to other types of road humps.

The levels of passenger discomfort reached a maximum of about 2 in the fire appliance and about 3 in the ambulance at speeds of about 20 to 25 mph. Discomfort remained the same or dropped at higher speeds. The fire appliance was driven over the humps at up to 37 mph and the crew generally felt that the level of discomfort was acceptable in an emergency situation. Two police cars were driven over the humps at speeds up to 55 mph. At 50 mph, the driver of the first experienced an acceptable level of discomfort for an emergency situation. The second police car grounded on the carriageway after leaving the 'H' ramp at 48 mph. This was considered to be due to the weight of equipment in the boot and the presence of a rear passenger. Following the trial the emergency services confirmed their support for the 'H' and 'S' hump designs.

Some runs with pedal cycles and a motorcycle were carried out. These were considered to be satisfactory but the motorcycle rider felt that the speed reducing effect on motorcycles would be minimal.

Fife Council considered that the trials had been successful in testing the proposed design of the 'H' and 'S' humps and, as the off-road trials had produced no particular safety concerns, the next stage was to proceed with on-road trials with some minor modifications to the ramp design (see Appendix B and Appendix C for the 'H' and 'S' hump designs). With the 'H' hump, it was decided that the width of the shallow kerbside ramp was insufficient and would encourage drivers to drive close to the kerb. The 'H' hump design for the on-road trials was amended with the ramp construction simplified by not including 'kerbs' to form the ramp. This resulted in an increase in the width of the shallow kerbside ramp of 100 mm to 800 mm, a decrease in the width of the shallow offside ramp of 50 mm to 650 mm and a decrease in the spacing between shallow ramps of 50 mm to 1950 mm. The 'S' hump design was amended in order to increase the differential effect on cars and buses by making the inner ramp shorter and steeper with a maximum gradient of 1 in 8 and the outer ramp longer and shallower with a minimum gradient of 1:33.

3.2.3 'H' and 'S' hump scheme in Glenrothes, Fife

Following the off-road trials, construction of both types of road hump was approved by the Scottish Office, for a trial period of 18 months, within the South Parks Road Traffic Calming Project in Glenrothes.

South Parks Road is a 2000 metres long local distributor road (and bus route) carrying about 10,000 vehicles per day. The carriageway is 6.8 metres wide, generally of straight horizontal and vertical alignment, with parking prohibited. The 85th percentile speed prior to traffic calming was about 38 mph. There were 14 personal injury and 39 damage only accidents resulting in 15 casualties in the 3 years before work on the scheme was started. The casualties were 3 serious and 12 slight. Seventy-three per cent of the total casualties were vulnerable road users.

The traffic calming scheme consisted of 3 'H' humps, 4 'S' humps along with cycleways and a number of mini-roundabouts. Two of the 'H' humps and two of the 'S' humps were combined with pedestrian crossings. Another 'S' hump was combined with a raised junction (see Figures 10 to 13). The scheme was constructed between March and June 1997 and the construction costs were about £2500 for an 'H' hump and £2000 for a 'S' hump. Fife Council found the construction of the 'S' hump 'surprisingly simple' after the initial setting out. The initial impression by Fife Council is that the humps have reduced the speed of cars and that buses are not unduly troubled.

Monitoring of the humps

TRL have been monitoring the operational performance of the scheme for CLT in conjunction with Fife Council. The ‘after’ monitoring was carried out in November 1997 and consisted of a week of automatic flow and speed measurements *between* humps in the same positions as the ‘before’ measurements, as well as radar speeds *at* and *between* the humps. In addition, video monitoring was carried out on one day between 8.00 and 12.00 to assess driver behaviour while crossing the humps.

Changes in vehicle flows and speeds (automatic measurements)

The traffic volume measurements showed that the average daily flows had been reduced from 9000 to 6000 vehicles per day (-33%) and that about 200 lorries and 100 buses are currently using the road daily.

The automatic speed measurements during morning and afternoon off-peak periods showed that the 85th percentile speed between the ‘H’ humps was reduced from 35 mph to 29 mph (-6 mph) and the 85th percentile speed between the ‘S’ humps was reduced from 38 mph to 30 mph (-8 mph). Ninety-seven per cent of vehicles were below 35 mph.

Vehicle speeds after installation (radar speed measurements)

Radar speeds were taken *at* and mid-way *between* an ‘H’ hump and an ‘S’ hump where the spacings were 120 metres and 110 metres respectively. Care was taken so that drivers were not aware of the radar gun being used as this may have reduced speeds to a lower level than usual for the road. The results are summarised in Table 6.

The speeds at the ‘H’ humps were similar to the speeds at the ‘S’ humps. Although only limited data for bus and goods vehicle speeds was available, it does indicate that goods vehicle speeds were within 2 mph of car speeds but bus speeds were about 5 to 6 mph lower than car speeds. On average, the mean speed of cars (about 22 mph) and buses (about 16.5 mph) at the ‘H’ and ‘S’ humps in Glenrothes are about 6 mph higher than the mean speed of cars and buses over 75mm high flat-top and round-top humps (Webster and Layfield, 1998).

Speeds midway between the ‘S’ and ‘H’ humps were higher than speeds at the humps by about 3 to 4 mph for cars, 1 to 3 mph for goods vehicles and 4 to 5 mph for buses. The 85th percentile speeds midway between the humps were below 30 mph for all three types of vehicles.

Driver behaviour at the humps

The video analysis of vehicles traversing an ‘H’ hump showed that the majority of vehicles crossed the hump without any major lateral deviation. However, three car drivers out of 843 observed (0.4%) drove down the centre of the road with half of the car in the opposing part of the carriageway and a further 2 car drivers crossed the centre line with their off-side wheels when traversing the hump. These manoeuvres occurred in the absence of oncoming traffic. No buses, lorries or vans (of the 26, 23 and 105 observed respectively) crossed the centre line while traversing the hump. Five motorcyclists were observed traversing the hump, 4 rode in the shallow near-side and one rode down the centre line of the road. There were 3 cyclists observed who all traversed the hump on the shallow near-side.

The video analysis of vehicles traversing an ‘S’ hump showed a similar pattern of driver behaviour to that at the ‘H’ hump. Two car drivers out of 1163 observed (0.2%) drove down the centre of the road with half of the car in the opposing part of the carriageway and a further car driver crossed the centre line with the off-side wheels when traversing the hump. Again, these manoeuvres occurred in the absence of oncoming traffic. No buses, lorries or vans (of the 64, 22 and 100 observed respectively) crossed the centre line while traversing the hump. All five motorcyclists observed kept to the left of the centre line of the road with 3 motorcyclists keeping to the near-side and 2 keeping to the off-side of the lane. There were 3 cyclists who were observed traversing the hump on the shallow near-side.

3.2.4 ‘S’ hump in Northampton

In April 1998, an ‘S’ hump was installed in Billing Brook Road, Northampton by Northamptonshire County Council. These replaced a set of 1880mm wide rubber cushions which were installed in July 1994 and had subsequently suffered from maintenance problems, as had the rest of the cushions along the road. The ‘S’ hump was installed on a

Table 6 Radar speeds (mph) on South Parks Road, Glenrothes

Type of hump	*Type of vehicle*	*Radar speed location*	*Sample size*	*Vehicle speed*		*Speed relative to car speed*	
				Mean	*85%*	*Mean*	*85%*
‘H’ hump	Car	At	502	21.8	26.6	-	-
	Goods veh.	At	12	20.0	25.0	-1.8	-1.6
	Bus	At	19	16.3	21.2	-5.5	-5.4
	Car	Between	502	25.9	29.5	-	-
	Goods veh.	Between	12	23.2	27.6	-2.7	-1.9
	Bus	Between	19	21.4	24.9	-4.5	-4.6
‘S’ hump	Car	At	504	21.9	26.4	-	-
	Goods veh.	At	10	22.6	28.3	0.7	1.9
	Bus	At	23	16.9	20.4	-5.0	-6.0
	Car	Between	504	26.2	29.8	-	-
	Goods veh.	Between	10	23.8	29.4	-2.4	-0.4
	Bus	Between	23	21.9	24.2	-4.3	-5.6

Figure 10 ‘H’ hump at a raised zebra crossing on South Parks Road, Glenrothes

Figure 11 ‘H’ hump ramps and drainage gullies on South Parks Road, Glenrothes

Figure 12 ‘S’ hump at a raised zebra crossing on South Parks Road, Glenrothes

Figure 13 ‘S’ hump at a raised junction on South Parks Road, Glenrothes

trial basis with a view to using more ‘S’ humps if it proved to be successful (see Figures 14 and 15). The dimensions of the ‘S’ hump used in Northampton were similar to those used by Fife Council except the hump plateau was shorter giving a total hump length of 10m compared to 11.5m in Fife. The width of the road was 7.3m.

Speeds over ‘S’ hump in Northampton

Radar speeds of cars and buses were taken on Billing Brook Road when the cushions were still in place and also after the cushions had been replaced with the ‘S’ hump. Both sets of measurements were made on a Tuesday between 11.30 and 14.00. A minimum of 200 car speeds were measured and a representative number of bus speeds (about 50 in total) were measured for comparison (see Table 7). All vehicle speeds measured were for free flowing vehicles in a northbound direction towards the nearby shopping centre.

The mean speed of buses at the 1880mm wide cushions (18.9 mph) was slightly higher than the mean car speed - by about 1.4 mph. The mean speed of buses at the ‘S’ hump (16.4 mph) was lower than the mean car speed by 2.6 mph.

The effect of changing from the 1880mm wide cushions to the ‘S’ hump was that the mean speed of cars was increased marginally by 1.5 mph to 19.0 mph and the mean speed of buses was reduced by 2.5 mph to 16.4 mph.

Comparison of speeds at ‘S’ humps in Northampton and Glenrothes, Fife

The mean bus speeds on the ‘S’ humps were similar at 16.9 mph in Fife and 16.4 mph in Northampton (northbound). The mean speeds for cars were higher in Fife at 21.9 mph compared with 19.0 mph in Northampton (northbound). In Northampton, the car speeds may have been influenced by the presence of pedestrians crossing the road to use the shopping centre. The results from the two schemes combined indicate that for ‘S’ humps the mean speed of cars is about 20.5 mph and the mean speed of buses is about 16.5 mph.

The ‘S’ hump does not offer a complete solution in terms of speed reduction. It appears that ‘S’ humps allow higher operating speeds for large buses than 75mm high humps, but lower operating speeds than cushions. Mean speeds of cars at the ‘S’ humps are similar to those at narrow width (1600mm) cushions thus, like narrow cushions, ‘S’ humps may not provide sufficient speed reduction in 20 mph zones without additional measures. ‘S’ humps could be usefully installed within a speed cushion scheme, where raised junctions or pedestrian crossing are required.

4 Summary and conclusions

The novel vertical deflections described in this report include sinusoidal profile humps, modified round-top and modified sinusoidal humps, ‘H’ humps and ‘S’ humps.

Sinusoidal humps

1 A review of reports from the Netherlands, Denmark and New Zealand indicate that sinusoidal humps are more comfortable for cyclists and car drivers than round-top or flat-top hump profiles, but little evidence was found as to the degree of difference in discomfort between the different hump profiles.

2 Sinusoidal humps are recommended by the Dutch traffic calming manual for use on roads with 20 kph speed limits and 30 kph speed limits. In the city of Enschede, sinusoidal humps reduced mean and 85th percentile speeds *at* the humps to 20 and 26 kph (12 and 16 mph) respectively.

3 The Dutch Regulations allow humps of 120 mm in height. In Great Britain, the Road Hump Regulations have a maximum hump height of 100 mm and experience with round-top humps suggests that sinusoidal hump heights of greater than 100 mm would cause grounding problems, particularly to cars with long wheelbases or low ground clearances (eg limousines and hearses). A maximum height of 75 mm is generally recommended in Great Britain.

4 In the city of Edinburgh, sinusoidal humps (100 mm high, 3.7 m long) have been installed on residential roads and informal feedback has been positive from cyclists. The mean and 85th percentile speeds *at* the humps have been reduced to 15.5 and 20 mph respectively. Mean speeds *between* the humps have been reduced to 22 mph for humps spaced 100m apart. These results are similar to those reported by Webster and Layfield (1996) in a study of 75 - 100 mm high round-top humps. Vehicle flows were reduced by an average of 23%.

Table 7 Radar speeds (northbound) at traffic calming measures on Billing Brook Road, Northampton

			Vehicle speed		*Speed relative to car speed*	
Type of hump	*Type of vehicle*	*Sample size*	*Mean (mph)*	*85% (mph)*	*Mean (mph)*	*85% (mph)*
Cushions	Car	200	17.5	22.3	-	-
Cushions	Bus	45	18.9	22.3	1.4	0.0
‘S’ hump	Car	200	19.0	23.3	-	-
‘S’ hump	Bus	34	16.4	19.7	-2.6	-3.6
Speed difference	Car	-	1.5	1.0	-	-
(‘S’ hump - Cushions)	Bus	-	-2.5	-2.6	-	-

Figure 14 ‘S’ hump at Billing Brook Road, Northampton

Figure 15 ‘S’ hump at Northampton showing the continuous curve between bus and car ramps

5 Track trials at TRL in October 1997, measuring passenger discomfort, have shown that compared with a round-top hump, a sinusoidal hump would produce a small reduction in discomfort for cyclists (both humps 75mm high and 3.7m long). The discomfort for cyclists crossing 75mm high flat-top humps was greater than that at the round-top hump and there was little difference in discomfort between flat-top humps with straight or sinusoidal ramps. Cyclists taking part in the tests indicated that the benefit gained with a sinusoidal hump was small and it was probably more important for Local Highway Authorities to ensure that there was no large upstand or discontinuity at the edge of a hump where it meets the road surface.

Modified round-top and sinusoidal humps

6 Feathering the leading edges of a round-top hump can have an important effect on the discomfort ratings for a given height hump. Feathering can therefore be used to lower the discomfort caused by a hump at a given speed in the same way that a reduced gradient can be used for flat-top humps.

7 Modified sinusoidal hump profiles have been used in Denmark. The profiles achieved are about midway between a round-top hump and 'true' sinusoidal hump and are similar to a round-top hump with feathered edges.

8 Round-top humps with feathered edges and modified sinusoidal humps (100 mm high, 9.5 m long) have been used on main roads through towns in Denmark with 50 kph (31 mph) speed limits. At schemes with the round-top humps, average speeds were reduced by about 6 mph to about 30 mph. Buses and lorries are expected to cross over at a speed about 9 mph lower than cars. The response from residents and road users was generally favourable, but there were some complaints about levels of vibration in properties near the humps. A 0.75m feathering was introduced to reduce the nuisance from large vehicles. A slightly smaller speed reduction of 4 mph was found during an on-road trial of modified sinusoidal humps.

9 Track trials at TRL in 1992, indicated that round-top humps with feathered edges (100 mm high, 10 m long which included a 1 m feathering at each edge) were not suitable for use on 40 mph speed limit roads because of the likelihood of buses grounding at speeds of 30 mph or more. Experience from Denmark, referred to above, suggests that such humps might be suitable for controlling speeds on 30 mph limit roads but other measures, such as speed cushions which reduce the discomfort experienced by occupants of buses and large commercial vehicles, may be a better option.

Flat-top humps with sinusoidal ramps

10 Several local highway authorities in England have used flat-top humps with 'rolled over' ramps at the top to reduce the sharp angle between the ramp and plateau and give an approximate sinusoidal profile. Speed measurements indicate that the mean vehicle crossing speeds may be slightly higher than predicted for conventional flat-top humps with 1:10 to 1:15 ramps.

'H' and 'S' humps

11 The principle of the 'H' or 'combi' hump was developed in Denmark as a result of trials which showed that it was possible to design a combined car and bus hump with two longer shallower outer profiles to take the tyres of buses and with a shorter inner profile for cars. The dimensions of the profiles could be chosen so that the car and bus speeds across the hump were comparable.

12 'H' humps have been used in the Danish town of Herning and Aalborg. In Aalborg there was single lane operation over the hump and a cycle lane bypass on both sides. The mean crossing speeds for cars and heavy vehicles were 25 kph (16 mph) and 20 kph (12 mph) respectively. The humps were acceptable to both bus drivers and passengers. The cost of the 'H' hump was about 4 to 5 times that of 9.5 metre long circular or sinusoidal humps.

13 Strathclyde Regional Council and Strathclyde Passenger Transport Executive carried out an off-road trial in 1992 of various hump profiles, including an 'H' hump, with a wide range of vehicles. The main purpose of the trial was to find 'H' hump dimensions which would be suitable for the British bus fleet. The results from the trials were encouraging and measurement of the bus rear axles showed that almost all the buses, with the exception of one of the mini-buses, could get at least the whole of the outer tyre of the twin rear wheels onto the outer shallower ramps.

14 In 1996, Fife Council carried out an off-road trial of 'H' and 'S' humps with a variety of vehicles including cars, buses, lorries and commercial vehicles. The objective of the trials was to design and test 'H' and 'S' humps suitable for bus and car use which would maintain speeds at 30 mph. The 'S' hump was developed by Fife Council in order to solve anticipated problems with drainage, construction and operational difficulties relating to the angular design of the 'H' hump. It works on a similar principle to 'H' humps but has a gradually varying ramp gradient across each lane rather than a marked lip between the car and bus ramps. The trials were considered successful and it was proposed to proceed with on-road trials with some minor modifications to ramp design and gradient.

15 In 1997, Fife Council installed a traffic calming scheme on South Park Road, Glenrothes, consisting of 3 'H' humps and 4 'S' humps. The construction costs were £2000 for an 'S' hump and £2500 for a 'H' hump. The 85th percentile speeds between the humps were reduced by about 7 mph to about 29.5 mph. The speeds at the 'H' humps were similar to those at the 'S' humps, with bus speeds about 5 to 6 mph lower than car speeds. On average, the mean speed of cars (about 22 mph) and buses (about 16.5 mph) are about 6 mph higher than the speeds of cars and buses over 75mm high humps. Video analysis indicated that few drivers (less than 0.5%) minimised their discomfort by driving down the centre of the road. Average daily vehicle flows were reduced from 9000 to 6000 vehicles per day (-33%).

16 In 1998, Northamptonshire County Council replaced a pair of 1880mm wide cushions with a ‘S’ hump in Northampton. The effect of changing from the 1880mm wide cushions to the ‘S’ hump was that the mean speed of cars was increased marginally by about 1.5 mph to 19 mph and the mean speed of buses was reduced by about 2.5 mph to about 16.5 mph. While the mean bus speed at the ‘S’ hump in Northampton was similar to that at the ‘S’ humps in Fife, the mean speeds for cars at the ‘S’ hump in Northampton was lower than that in Fife.

17 The ‘S’ hump does not offer a complete solution in terms of speed reduction. Initial results from the two schemes described above indicate that ‘S’ humps appear to allow higher operating speeds for large buses than 75mm high humps, but lower operating speeds than cushions. Mean speeds of cars at the ‘S’ humps are similar to those at narrow width (1600mm) cushions thus, like narrow cushions, ‘S’ humps may not provide sufficient speed reduction in 20 mph zones without additional measures. ‘S’ humps could be usefully installed within a speed cushion scheme, where raised junctions or pedestrian crossing are required.

5 Acknowledgements

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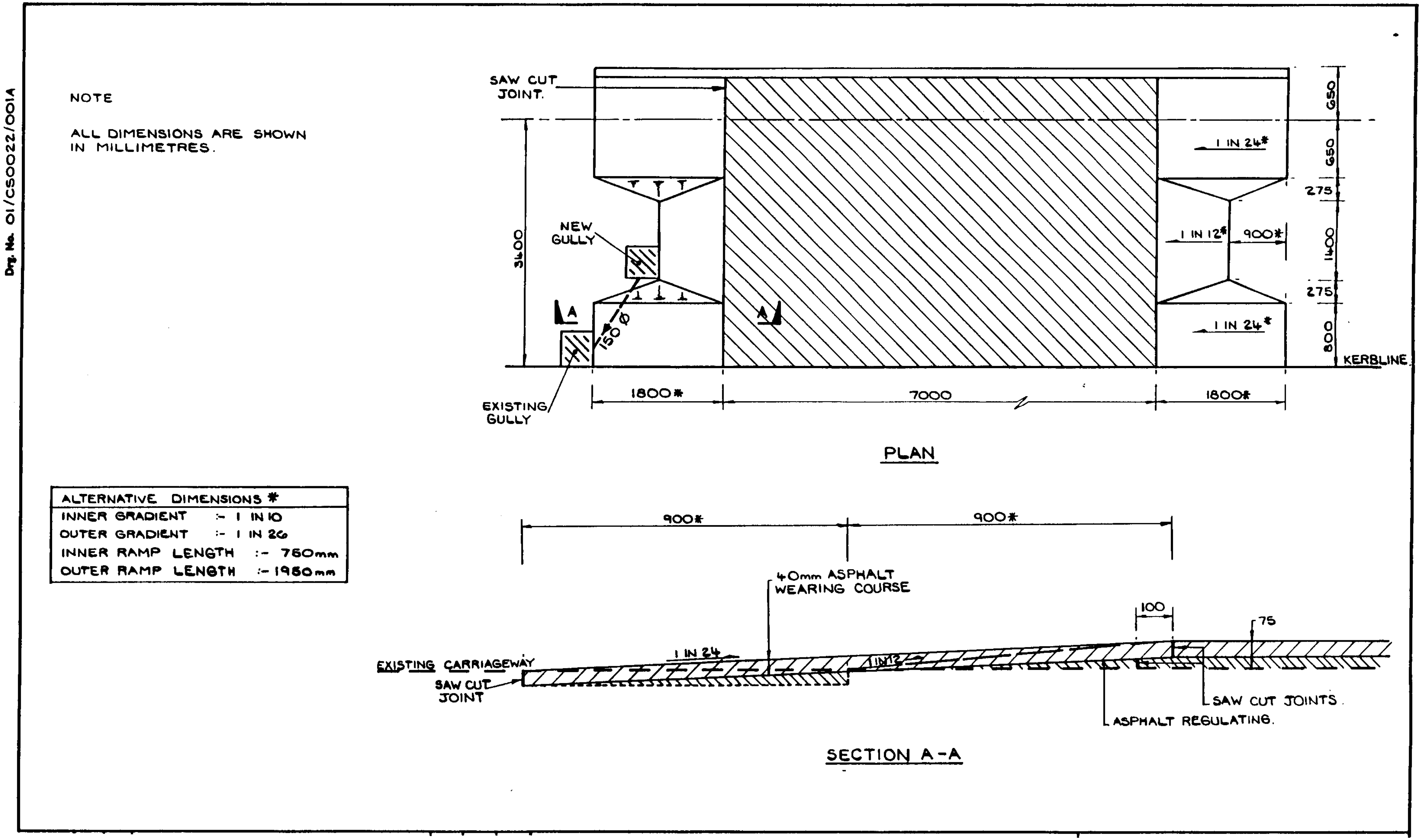
Appendix A: Table of various hump profile dimensions

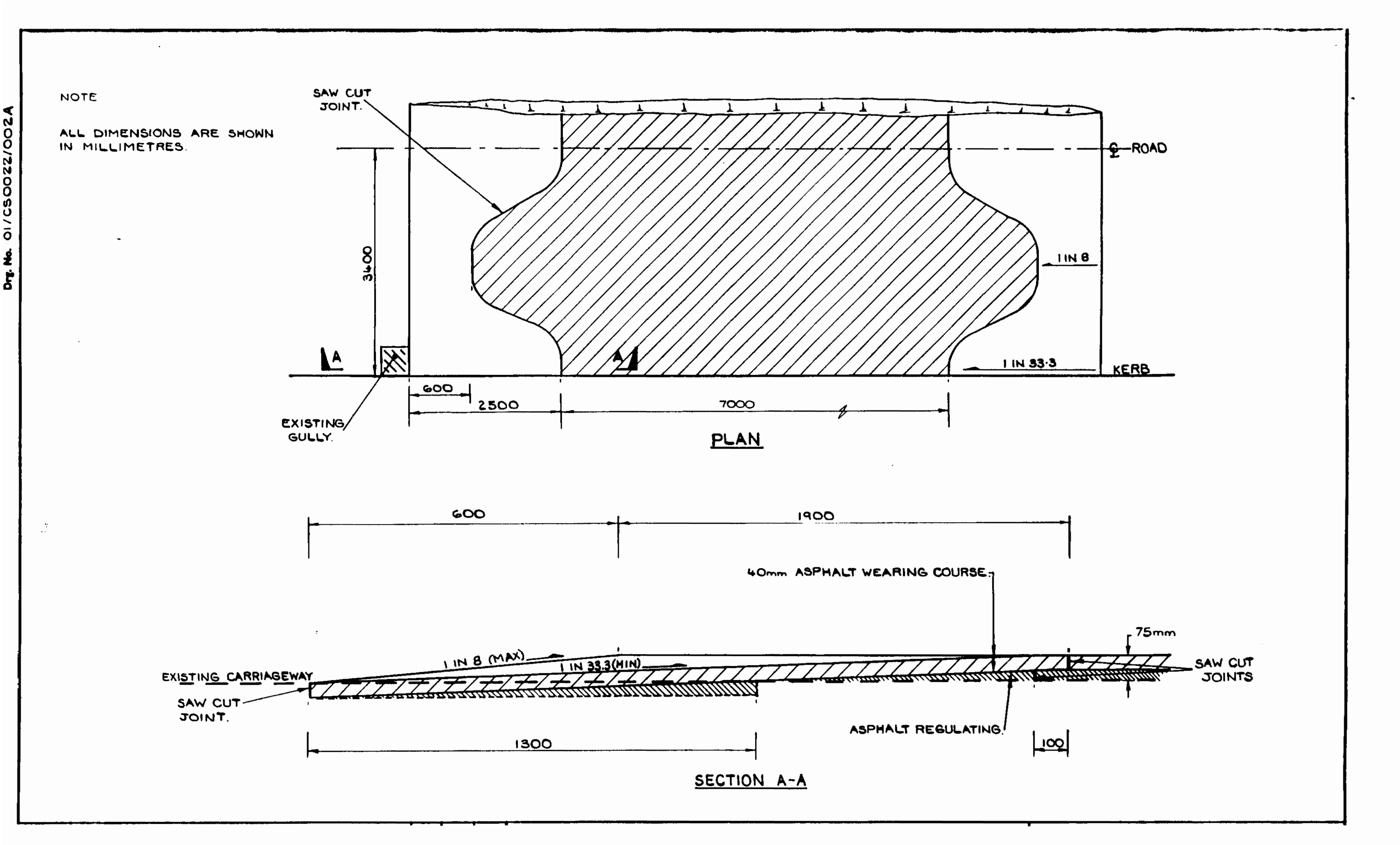
Length (cm)	*30kph (L=400cm, H=100mm)*			*40kph (L=650cm, H=100mm)*			*50kph (L=950cm, H=100mm)*		
	Circ	Sin	Mod sin	Circ	Sin	Mod sin	Circ	Sin	Mod sin
0	0	0	0	0	0	0	0	0	0
10	10	1	3	6	0	2	4	0	1
20	19	3	7	12	1	4	8	0	2
30	28	6	12	18	2	7	12	1	3
40	36	10	18	23	4	10	16	2	5
50	44	15	25	28	6	13	20	3	7
60	51	21	33	33	9	17	24	4	9
70	58	28	41	38	12	21	28	5	11
80	64	35	49	43	15	25	32	7	14
90	70	42	57	48	18	30	35	9	17
100	75	50	65	52	22	35	38	11	20
110	80	58	72	56	26	40	41	13	23
120	84	65	79	60	30	45	44	15	26
130	88	72	85	64	34	50	47	17	29
140	91	79	90	68	39	55	50	19	33
150	94	85	94	71	44	60	53	22	37
160	96	90	97	74	49	65	56	25	41
170	98	94	99	77	54	70	59	28	45
180	99	97	100	80	59	74	62	31	49
190	100	99	100	83	64	78	65	34	53
200	100	100	100	85	69	82	67	37	56
210				87	73	85	69	40	59
220				89	77	88	71	43	62
230				91	81	91	73	46	65
240				93	85	93	75	50	68
250				95	88	95	77	54	71
260				96	91	97	79	57	74
270				97	94	98	81	60	77
280				98	96	99	83	63	79
290				99	98	100	85	66	81
300				100	99	100	87	69	83
310				100	100	100	89	72	85
320				100	100	100	90	75	87
330				100	100	100	91	78	89
340							92	81	91
350							93	83	92
360							94	85	93
370							95	87	94
380							96	89	95
390							97	91	96
400							98	93	97
410							99	95	98
420							99	96	99
430							99	97	100
440							99	98	100
450							100	99	100
460							100	100	100
470							100	100	100

Circ = Circular profile, Sin = Sinusoidal profile, Mod sin = Modified sinusoidal profile (Lahrmann and Mathiasen, 1992)

Appendix B: Diagram of 'H' hump designed by Fife Council (Half carriageway width shown)



Appendix C: Diagram of 'S' hump designed by Fife Council (Half carriageway width shown)



Abstract

The original work on speed reducing road humps was carried out in the 1970's at TRL and was based on circular profile (round-top) humps of various dimensions. These track trials led to the adoption of the 'standard 3.7 metre long' circular profile hump which can be up to 100 mm high. Since the 1980's the regulations governing the use of road humps in Great Britain 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 and 100 mm in height and at least 900 mm long.

This report reviews some of novel or 'non-standard' hump profiles which have been used or trialed in the Netherlands, Denmark and Great Britain. Results have been obtained for sinusoidal humps, modified round-top humps and modified sinusoidal humps, flat-top humps with sinusoidal ramps, 'H' humps and 'S' humps.

Related publications

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)

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