



# **Impact of road humps on vehicles and their occupants**

**Prepared for Charging and Local Transport Division,  
Department for Transport**

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## Executive Summary

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A study has been undertaken by TRL and Millbrook Proving Ground for the Charging and Local Transport Division of the Department for Transport (DfT) to examine the impact of road humps on vehicles and their occupants. It involved practical testing of vehicles driven repeatedly over road humps, computer simulation of the road humps and vehicles, and biomechanical modelling of the human spine.

### Background

Road humps have been shown in a number of studies to reduce vehicle speeds and accident frequency. They are the most effective traffic calming device currently available and are likely to be in common use for some time. In general, levels of discomfort are higher when humps are traversed at higher speeds and therefore humps cause discomfort to vehicle occupants if their vehicle is travelling too fast. This increased discomfort is the mechanism which persuades drivers to slow down.

The widespread use of road humps has resulted in some members of the public complaining that humps cause long term damage to vehicle components, especially the suspension, and that they can cause damage to the undersides of vehicles with low ground clearance or to exhausts. Concern has also been raised about whether the use of road humps might cause or exacerbate spinal or other injuries.

Trials were undertaken several years ago for the majority of hump profiles used on public roads to ensure that if appropriate speeds are adopted, excessive discomfort to vehicle occupants does not occur. Similarly it was established from trials that damage will not occur to the undersides of vehicles if humps are designed in accordance with the regulations and advice, and are crossed at appropriate speeds.

Bus companies, however, suggest that bus routes with road humps lead to increased maintenance costs. Professional drivers claim that repeatedly driving over road humps does cause or exacerbate back injury. Bus passengers may find the quality of ride is worse on traffic calmed streets and (for a given speed) the discomfort experienced is greater than for car occupants, particularly as they do not have a seat belt. People with a mobility impairment may suffer extreme discomfort or pain when driving over humps even at low speeds.

Improving the safety of vulnerable road users is a primary objective of sustainable transport policies. Complaints concerning increased maintenance for vehicles and/or excessive discomfort for their occupants may inhibit the use of road humps and thus limit the measures available for reducing road accidents.

The study aimed to investigate objectively the possibility that road humps cause increased wear to vehicle components and injury to vehicle occupants, and to suggest how these problems, if they exist, can be ameliorated.

### Methodology

The study was based on:

- four different hump types, selected to be representative of those in common use (round top, flat top and sinusoidal humps, and a speed cushion), all 75mm high; and
- five different vehicle types, each representative of models currently found in the vehicle fleet (medium saloon car, London taxi, ambulance, single deck bus and minibus).

Practical vehicle testing at Millbrook Proving Ground was undertaken to determine whether repeatedly traversing road humps causes damage to vehicle components. The tests involved instrumenting the vehicles and recording the response of each vehicle when driven over the humps at different speeds, ranging from 10 to 40mph (10 to 25mph for the bus and the minibus), at 5mph intervals. Vehicle components were examined for possible damage after repeated traversing of the humps. The driver and either one or two passengers were asked to rate the discomfort of each hump at each speed for each vehicle.

One of the main outputs from the vehicle testing was the vertical acceleration recorded at different points in the vehicles. The peak vertical acceleration at a particular location in the vehicle (taken in this study as the average of the absolute maximum and minimum values) served as a measure of the discomfort felt by the vehicle occupants. Peak vertical acceleration has been shown to be strongly correlated with discomfort rating: for a given speed, the greater the vertical acceleration, the greater the discomfort. Earlier work has suggested that vehicle occupants are unwilling to accept a peak vertical acceleration greater than about 0.7g (where g is the force of gravity and equals 9.8m/s<sup>2</sup>).

The data were also used to validate the computer simulation and the biomechanical modelling at TRL. The computer simulation used a vehicle dynamics simulation model - SIMulation MODEL Non-linear or SIMON - running within Human Vehicle Environment (HVE). It had three purposes:

- to estimate acceleration values at different positions in the vehicle,
- to provide direct inputs to the biomechanical modelling if required; and
- to investigate the effects on vehicle occupants of a wider range of road hump profiles than was possible with the practical testing at Millbrook, with the potential for improving the situations where discomfort is greatest, without increasing the likely speed of traversal of other vehicles.

The biomechanical modelling was used to investigate the physical effect of road humps on vehicle occupants. TRL's existing model of the human spine was developed in order to estimate the forces in the spinal ligaments of a vehicle occupant when the vehicle traverses a hump, for a range of hump type / vehicle type / speed combinations.

## Effect of humps on the vehicle

The results for the vehicles tested were as follows:

- Visual inspections revealed no damage to any of the vehicles.
- Suspension geometry checks showed small changes in the toe (i.e. the difference between front and rear edges of tyres mounted on an axle) following the passes over the humps and these changes were outside the manufacturers' tolerances for the taxi, the ambulance and the minibus. When the tests were repeated at lower speeds, it was found that the changes remained within the tolerances, provided speeds did not exceed 25mph for the minibus or ambulance and 15mph for the taxi.
- Further investigation of the taxi, in which the forces generated when traversing the hump were simulated, showed that repeated traversals caused the toe to go outside the tolerances temporarily, but that subsequent traversals caused it to return within the tolerances. This suggests that the changes were due to deformation in the compliant elements within the suspension system of this particular vehicle (such as suspension arm bushes, control arm bushes, steering rack mounting, track rod ball joints etc), rather than being an early indication of vehicle damage.
- Four out of the five vehicles showed no change in damping performance following the tests. However, the ambulance showed a reduction in the front suspension damping ratios. As no change was seen in the dampers when tested off the vehicle, this result could be attributed to a reduction in the whole system damping, possibly due to minute changes in the rubber bushes. This represents a normal phenomenon in what was a fairly new vehicle rather than damage or accelerated degradation to the suspension.
- The forces generated by driving over humps at the speeds tested were found to be comparable with those sometimes experienced during normal driving activities, such as driving over a very irregular surface or a pothole, or mounting a kerb.

With the exception of the ambulance, the only changes found in the vehicle components were in the toe angle. The relatively small changes would not be noticeable to the driver in terms of the steering feel or handling, even where the tolerance band was exceeded.

Accelerated tyre wear is a possible effect of toe angle exceeding the tolerance, but it is considered that this would become noticeable to the driver only at greater deviations from specification than those seen during the tests. Since tyres are inspected at the annual MOT test, there is little chance of any defective condition developing that would go unnoticed. Vehicles require periodic adjustment of toe angle during correct maintenance, since driving over normal road features can give gradual toe angle change; that is why tyre centres and garages have the necessary equipment and have routinely carried out such checks during tyre changes for many decades, not just since road humps have become common.

## Discomfort experienced by vehicle occupants when traversing humps

For the vehicles tested in this study, the peak vertical acceleration was below 0.7g for the driver in the car and taxi over the round top, the flat top and the sinusoidal humps at 20mph and in the ambulance and minibus at 15mph, broadly corresponding to subjective ratings in the Millbrook testing of 'slightly uncomfortable' to 'uncomfortable'. Peak acceleration for the bus driver was slightly above 0.7g over the flat top and sinusoidal humps at 15mph. Values for the rear seat passenger were similar to those for the driver in the car at 20mph and the minibus and bus at 15mph.

The peak acceleration for the passenger in the rear of the taxi was much greater (and reported discomfort was also substantially higher) than for the driver, even at 15mph. This may be due to the leaf spring suspension in the taxi tested; the latest models are believed to have coil springs. In the ambulance, the peak acceleration was slightly greater for the passenger in the rear crew seat than for the driver at 15mph, with a much greater differential at higher speeds. Of the full width humps, the flat top hump was better than either the round top or the sinusoidal for the passenger.

The peak vertical acceleration over the cushion was well below 0.7g for both driver and rear seat passenger in most vehicles. For the rear passenger in the taxi and the ambulance, the peak acceleration was higher than for the driver, but still less than for full width humps; straddling the cushion was more comfortable than traversing it with two wheels on. In the trials, the passenger in the ambulance experienced little discomfort when straddling the cushion.

It was concluded that the levels of discomfort associated with measured peak vertical acceleration were generally acceptable if the humps were traversed at appropriate (intended) speeds i.e. not exceeding 15 to 20mph. Although passengers in the rear of taxis suffer considerably more discomfort than drivers, experienced taxi drivers are well aware of this and tend to approach road humps at very low speeds. Ambulance drivers will act in accordance with the situation.

Of the profiles tested, the sinusoidal hump tended to give the highest peak vertical accelerations, but in most cases these were only slightly higher than with the round top hump. Humps with a sinusoidal profile are similar to round top humps but have a shallower initial rise. They were developed in the Netherlands and Denmark to provide a more comfortable ride for cyclists in traffic calmed areas.

## Possible alternative hump profiles from HVE computer simulation

From the HVE computer simulation, there was no evidence that alternative hump dimensions to those currently recommended could remove any unnecessary discomfort *and* maintain safety objectives. The following hump dimensions were considered optimal of those tested, in the sense of maximising discomfort to car drivers at speeds above 20mph:

- A height of 75mm. This was shown in earlier studies to be a good compromise between effectiveness and possible grounding.
- A round top hump length of 3.7m.
- A flat top hump plateau length of 6m to 9m and a ramp gradient of 1:13 to 1:15.
- A speed cushion length of 3.0m, with 1.8m plateau length, 1:4 side ramp gradient, 1.7m width, 1.1m plateau width and 1:8 gradient of on/off ramps.

### **Biomechanical modelling of effect on spine for a vehicle occupant when traversing humps**

In terms of possible damage to the spine, the ligament forces were considered appropriate for assessing injury and causation of pain. From the biomechanical modelling, it was found that:

- Predicted spinal ligament forces were almost an order of magnitude smaller than the damage threshold for such ligaments.
- Predicted forces transmitted through the spine as a whole were at least a factor of 4 smaller than those generated in discs by heavy lifting.

Medical opinion was sought to assist in the interpretation of these results. Because the predicted ligament forces were so far below the damage threshold, it was concluded that ligaments are unlikely to be injured by traversing road humps. Although muscle tissue was not modelled explicitly, this fact can also be taken to imply that the muscles would also be very unlikely to be damaged under the predicted loads.

Similarly, the predicted forces on discs were such that a healthy spine is unlikely to be injured by repeated traversing of a road hump and vertebral fractures are very unlikely to occur for those with normal bones.

Based on these predictions, it is considered that vehicle occupants are very unlikely to be injured as a result of single or repeated traversing of road humps. The exceptions to this statement are people with pre-existing conditions that result in either degenerated discs or weak bones, in which case they could be more susceptible to injury depending on the seriousness of their condition.

### **Recommendations**

- Vertical traffic calming measures (road humps and speed cushions) should continue to be used as an effective method of reducing vehicle speeds, preventing injuries and saving lives. The existing guidance on road hump design should not be altered.
- Where vertical traffic calming measures are required on bus and ambulance routes, speed cushions rather than standard road humps should be used.
- Vehicles should be prevented from parking near to speed cushions to enable buses and ambulances to straddle the cushions (since discomfort is greater when such vehicles are forced to mount the cushion).

- Taxi design needs to be improved to increase comfort in the rear – this is likely to have a general benefit, particularly for elderly people and those with certain disabilities, but would be especially beneficial in areas with road humps.
- Similarly, ambulance design could be improved to increase comfort in the rear. In particular, the use of vehicles with single rather than double rear wheels would be preferable.
- Road humps need to be carefully built to specification as earlier work has shown that quite small deviations can adversely affect the comfort of vehicle occupants. This is particularly true of the profile at the transition from road to hump.
- Careful attention needs to be paid to the signing and marking of road humps to ensure their visibility, especially at night, and to encourage drivers to slow down in good time for them.



# 1 Introduction

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A study has been undertaken by TRL and Millbrook Proving Ground for the Charging and Local Transport Division of the Department for Transport (DfT) to examine the impact of road humps on vehicles and their occupants. It involved testing of vehicles driven repeatedly over road humps, computer modelling of the road humps and vehicles, and biomechanical modelling of the human spine.

## 1.1 Background

Road humps have been shown in a number of studies to reduce vehicle speeds and accident frequency (see e.g. Webster and Mackie, 1996). They are the most effective traffic calming device currently available and are likely to be in common use for some time. In general, levels of discomfort are higher when humps are traversed at higher speeds and therefore humps cause discomfort to vehicle occupants if their vehicle is travelling too fast. This increased discomfort is the mechanism which persuades drivers to slow down.

The widespread use of road humps has resulted in some members of the public complaining that humps cause long term damage to vehicle components, especially the suspension, and that they can cause damage to the undersides of vehicles with low ground clearance or to exhausts. Concern has also been raised about whether the use of road humps might cause or exacerbate back or other injuries.

Trials were undertaken several years ago for the majority of road hump profiles used on public roads to ensure that if appropriate speeds are adopted, excessive discomfort to vehicle occupants does not occur (Sayer *et al.*, 1999). Similarly it was established from trials that damage will not occur to the undersides of vehicles if humps are designed in accordance with the regulations (DfT, 1996A and 1999) and are crossed at appropriate speeds.

Bus companies, however, suggest that bus routes with road humps lead to increased maintenance costs. Professional drivers claim that repeatedly driving over road humps does cause or exacerbate back injury. Bus passengers may find the quality of ride is worse on traffic calmed streets and (for a given speed) the discomfort experienced is greater than for car occupants, particularly as they do not have a seat belt; they may experience difficulties when standing or moving along the bus as it traverses a hump. People with a mobility impairment may suffer extreme discomfort or pain when driving over humps even at low speeds.

Improving the safety of vulnerable road users is a primary objective of sustainable transport policies. Complaints concerning increased maintenance to vehicles and/or excessive discomfort for their occupants may inhibit the use of road humps and thus limit the measures available for reducing road accidents.

The study aimed to investigate objectively the possibility that road humps cause increased wear to vehicle components and injury to vehicle occupants, and to suggest how these problems, if they exist, can be ameliorated.

## 1.2 Road hump design

Since the 1980s, 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. The current regulations (DfT, 1999) do not specify an exact hump profile providing the humps are within certain restrictions (between 25mm and 100mm in height and at least 900mm long, with no vertical face exceeding 6mm).

The different hump profiles used on the public road generate different levels of discomfort for a given vehicle type and speed (Sayer *et al.*, 1999). In general, a hump profile that generates a lower level of discomfort will allow higher vehicle speeds. The main parameters in road hump design are height, length and on/off ramp gradient (also width and side ramp gradient for speed cushions). Speed cushions that can be straddled by the front wheels of large vehicles are more appropriate for routes regularly used by buses or emergency vehicles.

## 1.3 Vehicles traversing road humps

A vehicle traversing a hump will be affected by factors such as:

- Design of hump.
- Vehicle type.
- Vehicle characteristics.
- Condition and age of vehicle.
- Condition of vehicle's shock absorbers.
- Loading of vehicle.
- Driver characteristics.
- Speed across hump.
- Braking before hump.
- Frequency of traversing hump.
- Angle across hump.

## 1.4 Occupants of vehicles traversing road humps

### 1.4.1 Ride comfort

Ride comfort for vehicle occupants when the vehicle traverses a hump depends on all of the vehicle factors (Section 1.3) and also on:

- Position in the vehicle.
- Seat structure and padding.
- Tolerance of people with back pain or disability to vehicle oscillations.

Peak vertical acceleration is an important determinant of discomfort when sitting in a moving vehicle. In Danish research, Kjemtrup (1990) found that values up to about 0.7g (where g is the force of gravity and equals 9.8m/s<sup>2</sup>) are tolerated and that hump profiles should be capable of generating values higher than 0.5g for effective speed reduction.

### 1.4.2 Professional drivers and bus passengers

Professional drivers are subject to vibration during the course of their work and this has been associated with

problems of back pain in unpublished research by TRL. Vertical deflections such as road humps are likely to add to the vibration dose. This might be exacerbated by driving across the humps at inappropriate speeds (e.g. if they are trying to keep to a schedule).

Bus drivers are potentially at greater risk than other drivers if road humps have to be negotiated frequently during a driving shift. Bus passengers are likely to experience fewer hump crossings than bus drivers but they generally have less comfortable seats and do not have direct control over the speed at which the humps are crossed. Sitting over the back wheel or at the rear of the bus may be particularly uncomfortable. Although the front wheels of buses avoid cushions, it is not always the case that the back wheels do so and this will affect bus passengers' comfort. In addition, parked vehicles can prevent buses from straddling cushions.

### 1.4.3 People with a mobility impairment

In recent years, there have been significant advances in the availability of wheelchair accessible transport and in the United Kingdom people can now travel, while seated in their wheelchairs, in taxis, buses, coaches, minibuses, trams and trains. They can also drive from their wheelchair in appropriately modified vehicles (typically adapted cars, multi-purpose vehicles and van conversions). Accessibility regulations under the 1995 Disability Discrimination Act will ultimately ensure that all forms of land-based public transport are accessible to wheelchair users and will require operators to provide for people to travel in their wheelchairs.

Many people with disabilities have conditions that cause chronic pain and discomfort (e.g. arthritis, multiple sclerosis, back pain), and an uneven road surface can exacerbate such conditions and sometimes restrict a person's mobility by preventing their use of certain roads and thus limiting access to certain areas. General ageing may lead to joint problems.

Vehicles used to transport people with a mobility impairment, such as minibuses or ambulances, may be less comfortable than cars if driven over road humps at speed. Ambulances may have to transport people with suspected spinal injuries.

## 1.5 Project objectives

The objectives of the project were to determine scientifically the effect of repeated driving over road humps on:

- The condition of the vehicle:  
Is there damage or greater wear than might normally be expected?
- The vehicle occupant:  
Can road humps cause or exacerbate back injuries to drivers or passengers?

and to make recommendations as to what might be done to lessen vehicle damage and occupant injury while maintaining safety performance. Passengers include those with a mobility impairment requiring the use of a wheelchair and those with a disability likely to cause pain and discomfort.

## 2 Methodology

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### 2.1 Overview

The study was carried out using a combination of practical vehicle testing at Millbrook Proving Ground, and vehicle simulation and biomechanical modelling of the human spine at TRL. The simulation used an existing vehicle dynamics simulation model - Simulation MOdel Non-linear or SIMON - running within Human Vehicle Environment (HVE).

The aims of the vehicle testing were to:

- determine whether repeated traversing of road humps causes any damage to vehicle components;
- validate the HVE simulation data;
- provide input to the model of the human spine used to estimate the effect on the vehicle occupant.

One of the main outputs from the practical testing was the vertical acceleration recorded at different points in the vehicle. The peak vertical acceleration at a particular location in the vehicle (taken as the average of the absolute maximum and minimum values) served as a measure of the discomfort felt by the occupants. Peak vertical acceleration has been shown to be strongly correlated with discomfort rating: for a given speed, the greater the vertical acceleration, the greater the discomfort (see Section 1.4.1).

The HVE modelling work was used:

- to estimate the tri-axial acceleration values at different positions in the vehicle;
- to provide direct inputs to the biomechanical modelling; and
- to investigate the effects on vehicle occupants of a wider range of road hump designs (dimensions) than was possible in the practical testing at Millbrook.

The biomechanical modelling was used to investigate the effect of road humps on vehicle occupants. TRL's existing model of the human spine was developed in order to estimate the forces in the spinal ligaments of a vehicle occupant when the vehicle traverses a hump, for a range of the hump type/vehicle type/speed combinations. Medical opinion was sought to assist in the interpretation of the results.

### 2.2 Scope of study

#### 2.2.1 Review and consultation

The international transport research database of published literature (ITRD) was searched to investigate the effect of road humps on professional drivers, bus passengers and those with a mobility impairment. The search was extended to the Web, and a national press cutting search, to identify published literature and anecdotal information. A broad range of organisations, including vehicle manufacturers, professional bus and taxi drivers, bus operators, the County Surveyors Society (CSS), organisations representing older people or people with disabilities, the Mobility and Inclusion Unit (DfT) was consulted.

This exercise led to the extension of the vehicle testing from 3 vehicles (car, taxi, bus) to 5 (car, taxi, bus, ambulance, minibus).

### 2.2.2 Vehicle type

Five different vehicles were tested, as shown in Figures 1 to 5, a medium sized car (Vauxhall Astra), a London taxi (LTI TX1), an ambulance, a single deck bus and a minibus. Their characteristics are summarised in Table 1.



**Figure 1** Medium-sized car (Vauxhall Astra)



**Figure 2** London taxi



**Figure 3** Ambulance



**Figure 4** Single deck bus



**Figure 5** Minibus

**Table 1** Description of vehicles

<i>Vehicle</i>	<i>Make</i>	<i>Year of registration</i>	<i>Mileage prior to testing</i>	<i>Front suspension</i>	<i>Rear suspension</i>
Medium-sized car	Vauxhall Astra	2001/2002	1,660	Coil springs	Coil springs
London taxi	LTI TX1	2000/2001	23,745	Coil Springs	Leaf springs
Ambulance	Modular/ Ford Transit	2001	2,316	Coil springs	Air
Single deck bus	Volvo/Robert Wright	1996	15,247	Air	Air
Minibus	Vauxhall Movano	2000/2001	2,871	Coil springs	Leaf springs

### 2.2.3 Road hump design

Four types of vertical deflection were used in the testing at Millbrook – a round top hump, a flat top (platform) hump, a sinusoidal hump and a speed cushion, with dimensions as in Table 2. Sufficient space was provided for vehicles to turn and to get up to speed before reaching each hump and to brake safely afterwards. All the humps were 75mm high. This height has been adopted by many highway authorities in the UK as it provides a good compromise between speed reduction and hump severity. Photographs of the humps are shown in Figures 6 to 9. The same hump designs were used in the HVE modelling (Section 4) and the biomechanical modelling (Section 5). Further road hump designs were tested in the additional HVE modelling described in Section 4.6.

**Table 2 Dimensions of humps tested**

<i>Hump dimensions (all height 75mm)</i>	
<b>Round top hump<sup>1</sup></b>	
Length	3700mm
Minimum width	3400mm
<b>Flat top hump<sup>1</sup></b>	
Plateau length	6000mm
Gradient of plateau	1 in 15 (straight on/off ramps)
Minimum width	3400mm
<b>Sinusoidal hump<sup>1</sup></b>	
Length	3700mm
Minimum width	3400mm
<b>Speed cushion</b>	
Width	1700mm
Plateau width	1100mm
Gradient of side ramps	1 in 4
Length	3000mm
Plateau length	1800mm
Gradient of on/off ramps	1 in 8

<sup>1</sup> Excluding edges tapered for safety.



**Figure 6 Round-top hump**



**Figure 7 Flat-top (platform) hump**



**Figure 8 Sinusoidal hump**



**Figure 9 Speed cushion**

### 2.2.4 Vehicle speeds across humps

A range of speeds was used for the testing, from 10 to 40mph at 5mph intervals for the car, taxi and ambulance. It was initially intended to limit the range 10 to 25mph for the bus and minibus. In the event, a small number of runs were carried out at speeds up to 40mph for these vehicles.

### 2.2.5 Vehicle occupants

The testing included acquisition of data from an accelerometer on the driver's seat and from an instrumented Hybrid III dummy in a rear seat. The bus also carried a wheelchair with a (non-instrumented) dummy. Checks were made to see whether the unrestrained wheelchair stayed in position on the bus. (Wheelchairs are not restrained in buses, but are positioned in dedicated areas designed to limit the movement of the wheelchair; it is also recommended that the brakes are applied).

## 3 Vehicle testing by Millbrook

### 3.1 Introduction

The testing by Millbrook was intended to determine whether repeatedly traversing road humps causes damage to vehicle components. In summary, the tests involved instrumenting the vehicles to be tested and recording the response of each vehicle and its occupants over the road humps at a range of speeds.

Millbrook hired or was loaned the vehicles. These were to MOT standard and were carefully checked before use for any unusual wear/damage, particularly relating to suspension components and steering geometry.

The humps were purpose-built of concrete to a design tolerance of  $\pm 3$ mm. The accuracy of each hump profile was verified using TRL's 3D laser scanning system.

### 3.2 Methodology

#### 3.2.1 Vehicle specification and initial condition

A number of measurements were made to record the specification and condition of each vehicle on arrival:

- Total mass.
- Overall length and width.
- Wheelbase.
- Front / rear track width inner / outer.
- Front / rear overhang (measured from wheel centre).
- Maximum positive / negative suspension deflection – front/rear.
- Front / rear loaded tyre radius at test weight.
- Mass of wheels.

All measurements were made with a full tank of fuel and with the tyres inflated to the manufacturers' recommended cold inflation pressures.

### 3.2.2 Static measurements

*Steering geometry and suspension component characteristics*  
Front and rear wheel alignment measurements were taken prior to, during and following the dynamic testing to monitor any variation in the vehicle's suspension geometry. The main parameters of interest were camber, caster and toe. (The toe is the difference between front and rear edges of tyres mounted on an axle. Toe-in means the front edges are closer together than the rear edges and the tyres point inwards. Toe-out means the front edges are further apart than the rear edges and the tyres point outwards.) Tolerances for the total toe measurements were monitored against manufacturer specifications.

The front and rear static spring rates of each vehicle were measured before and after the dynamic testing. The dampers were removed from each test vehicle and subjected to carding tests. Drop tests were conducted on both front and rear suspensions to demonstrate damping properties for the whole suspension system. Damping ratios were calculated for each wheel.

#### *Seat characteristics*

The characteristics (static stiffness) of the driver and rear passenger seats were measured at four different positions and the results averaged.

### 3.2.3 Dynamic testing procedure

The physical test programme utilised Millbrook's in-house professional test drivers. The drivers were instructed to approach the humps at a speed as close as possible to the test speed, without applying acceleration or braking as the vehicle crossed the hump, with the angle of vehicle travel across the hump 90 degrees.

#### *Vehicle instrumentation*

For the dynamic tests, each vehicle was fitted with a number of sensors linked to a Data Acquisition Recorder, set up to record all channels simultaneously. A sampling rate of 500Hz was selected in order to obtain smooth results without generating too much data. The instrumentation included a multi-axis motion sensor, tri-axial seat pad, plus various strain gauges, accelerometers and displacement transducers (Table 3).

Each vehicle was loaded with an instrumented Hybrid III 50%ile (75kg) test dummy, which was positioned in a passenger seat in the rear of the vehicle (in the furthest row back, in vehicles where there was more than one row of seats). The dummy wore a seat belt in all vehicles except the bus. A second (non-instrumented) dummy was used in a wheelchair in the bus and on a stretcher in the ambulance.

**Table 3 Vehicle instrumentation**

Motion sensor:	Measures tri-axial acceleration and roll, pitch and yaw angle and angular rate
Seat Tri-axial Accelerometer:	Seat pad on driver's seat with built-in accelerometer.
Vehicle data logging:	Strain gauges on critical points of body and suspension, accelerometers on front and rear axles and displacement transducers on each wheel.
Measurements on Hybrid III test dummy in rear seat:	Upper and lower spine load cell recordings.

Up to 32 data channels were employed, logging acceleration, displacement, load and vehicle attitude for example:

- CoG longitudinal, lateral and vertical acceleration.
- Driver's seat longitudinal, lateral and vertical acceleration.
- Vehicle pitch angle and pitch rate.
- Vehicle roll angle and roll rate.
- Vertical displacement of each wheel.
- Longitudinal and vertical acceleration at each wheel.

#### Outline of testing

The sequence of dynamic testing was undertaken in 3 stages (Table 4):

- 1 Measurement (instrumented) runs over the round top, sinusoidal and flat top humps at each speed specified for the particular vehicle.
- 2 Measurement and durability runs over the cushion (straddling and with two wheels on) .
- 3 Durability runs over the round top, flat top and sinusoidal humps.

Between each stage, a visual inspection was undertaken and the suspension geometry was checked and reset if necessary.

Evidence of any gradual cumulative suspension deterioration resulting from the tests was considered by a comparison of the measurements of steering geometry and basic, *in-situ*, suspension component characteristics such as static spring rates and suspension damping ratio, made before and after the full set of tests on each vehicle (Section 3.2.2).

However, deterioration of the vehicle due to hump traversing (as opposed to sudden damage due to abusive driving) was not anticipated since it would only be expected after a number of hump passes that is orders of magnitude higher than the number of hump passes included in this project.

#### Measurement (instrumented) runs

Five measurement runs were undertaken at each speed (10, 15, 20, 25, 30, 35 and 40mph) over the flat top, round and sinusoidal humps, except that only two tests were conducted for the bus and minibus at speeds of 30mph and above.

A similar set of measurement runs was undertaken over the speed cushion, firstly with the vehicle straddling and then with two wheels on. For the latter, 2 runs were performed with the driver's side up and 3 with the passenger's side up at each speed.

#### Durability runs

A speed of 30mph was adopted for durability runs for the car, taxi and ambulance. Lower speeds would be unlikely to show any wear, and higher speeds would have been above the speed limit for any road on which humps may be installed without special authorisation. The speed selected for the bus and minibus was 25mph, initially intended to be the maximum tested.

For each vehicle, 85 runs were completed straddling the cushion and 85 with two wheels on. For the latter, the passenger side only was driven over the cushion to increase the exposure to wear/damage. A further 85 durability runs were then undertaken over each of the flat top, sinusoidal and round top humps.

**Table 4 Sequence of dynamic testing**

<i>Test</i>	<i>Speed</i>	<i>No. of passes</i>
Geometry check 1 – pre-testing		
<i>Measurement runs</i>		
Flat top hump	10-40mph <sup>1</sup> (5mph increments)	35 total <sup>2</sup> (5 at each speed)
Round hump	10-40mph <sup>1</sup> (5mph increments)	35 total <sup>2</sup> (5 at each speed)
Sinusoidal hump	10-40mph <sup>1</sup> (5mph increments)	35 total <sup>2</sup> (5 at each speed)
Geometry check 2		
<i>Measurement runs</i>		
Cushion – straddled	10-40mph <sup>1</sup> (5mph increments)	35 total <sup>2</sup> (5 at each speed)
Cushion – 2 wheels on	10-40mph <sup>1</sup> (5mph increments)	35 total <sup>2</sup> (5 at each speed)
<i>Durability runs</i>		
Cushion – straddled	30mph <sup>3</sup>	85
Cushion – 2 wheels on	30mph <sup>3</sup>	85
Geometry check 3		
<i>Durability runs</i>		
Flat top hump	30mph <sup>3</sup>	85
Round hump	30mph <sup>3</sup>	85
Sinusoidal hump	30mph <sup>3</sup>	85
Geometry check 4		

<sup>1</sup> 10-25mph for bus and minibus.

<sup>2</sup> 26 for the bus and minibus.

<sup>3</sup> 25mph for bus and minibus.

### Video photography

Video photography was used to record a typical approach to each hump for each vehicle (side and front) and the lateral position of vehicles traversing the speed cushion. Still photographs were taken where appropriate.

### Subjective ratings of comfort

Subjective ratings of comfort by the driver and one or two passengers were recorded on a scale of 0 (comfortable) to 6 (very uncomfortable) for each vehicle/speed/hump combination (Table 5). This was intended to facilitate subsequent subjective-objective correlation. Clearly the results obtained are based on too small a sample to be robust, but they are indicative of the likely effects on vehicle occupants.

**Table 5 Subjective comfort ratings**

Rating	Occupant comfort
0	Comfortable
1	
2	Slightly uncomfortable
3	
4	Uncomfortable
5	
6	Very uncomfortable

## 3.3 Results

### 3.3.1 Car

#### Vehicle condition and static testing

The car tested was a 1.6 litre Vauxhall Astra with a ‘51’ registration number (2001/2002). At the start of the trials, it had 1660 miles showing on the odometer.

No damage was observed from the visual inspections. During the wheel alignment checks, suspension geometry did show small changes in the total toe, as shown in Table 6 (which summarises the tests for all vehicles). For the car, the total toe (see Section 3.2.2) was initially on the limit of the manufacturer’s tolerance and just outside it after the measurement runs. However, the change was well within the normal range and was therefore not considered to be of significance.

Overall, the comparison of the pre- and post-test static measurements showed no evidence of any suspension degradation from a total of 600 runs over the road humps.

### Vertical acceleration

Figure 10 shows the vertical acceleration traces measured at the centre of gravity as the car made five traverses across the flat top hump at 30mph (pictures generated from HVE/SIMON simulation –see Section 4). The start time of the trace was just in advance of the vehicle reaching the hump and varied slightly for each run. The five runs at 30mph have been re-calibrated to the same start point and are then seen to be very consistent. This consistency between runs was generally found to be the case across the different hump profiles and different speeds tested.

The first two peaks, at about 0.3 and 0.5 seconds respectively, occur as first the vehicle’s front wheels and then the back wheels mount the hump. The trough at about 0.7 to 0.8 seconds occurs as the vehicle leaves the hump. Subsequent peaks and troughs show the damping after the vehicle has left the hump.

Figures 11a-c show the variation with speed of the average absolute maximum and minimum vertical acceleration at the centre of gravity, at the driver’s seat and in the load cell in the pelvis of the dummy seated in the rear passenger seat for the flat top, round top and sinusoidal humps respectively. In general, differences between the acceleration experienced by the driver and dummy will be due to different positions in the vehicle, different seating and different locations of the two accelerometers (under the driver and in the pelvis of the dummy); the latter effect was shown to be small (see Section 5.3). For the car, there was little difference either between their positions relative to the centre of gravity or seating and therefore values obtained were relatively similar.

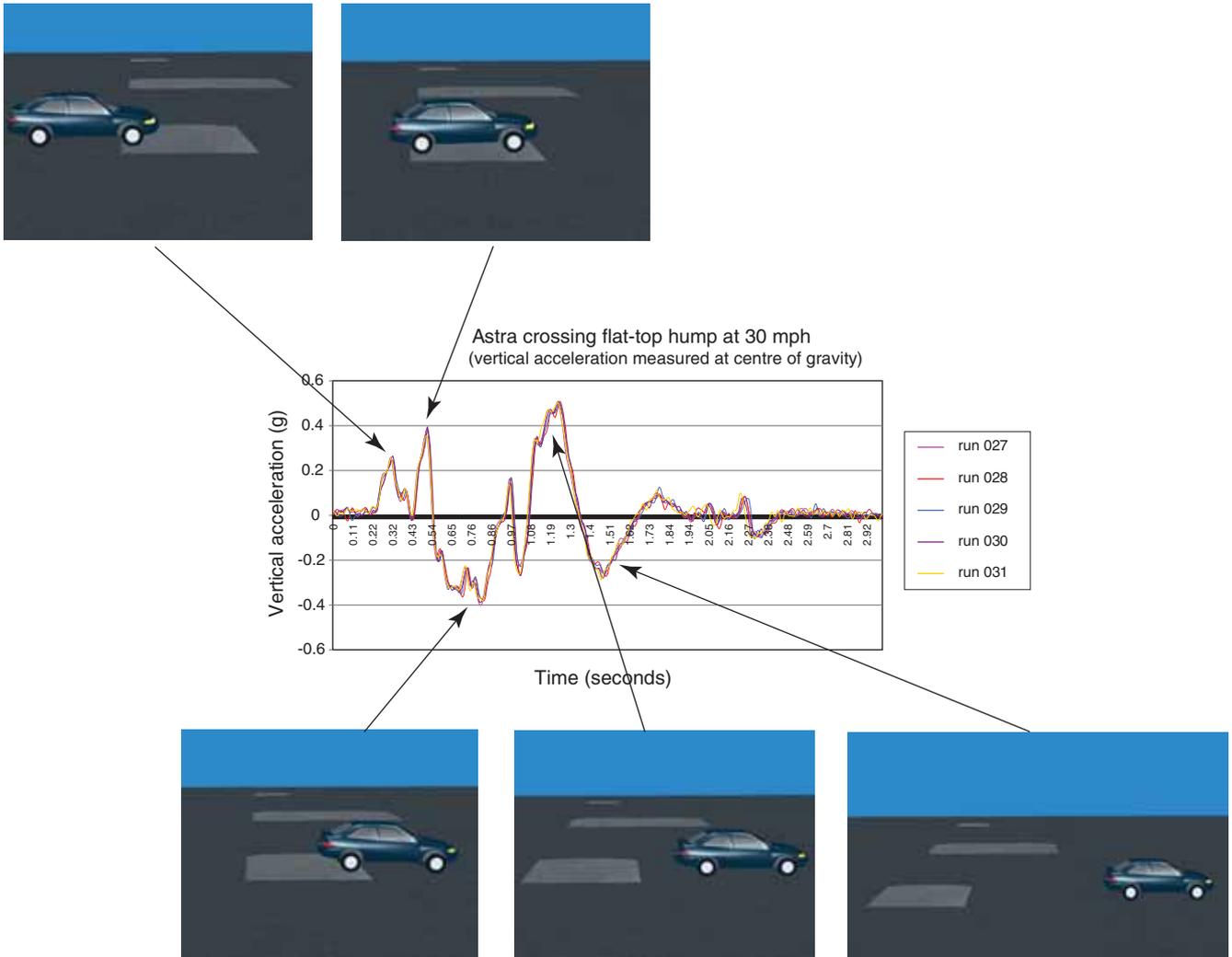
The average absolute maximum and minimum vertical acceleration was plotted in preference to the peak vertical acceleration since it was found that sometimes the peak (maximum) vertical acceleration was the larger in magnitude and sometimes the minimum, depending on the speed of the vehicle and the hump profile. In previous studies, both measures of vertical acceleration have been found to be closely correlated with subjective assessments of passenger discomfort, with the average absolute maximum and minimum vertical acceleration giving slightly better fits to the data.

**Table 6 Summary of changes in total toe from wheel alignment checks**

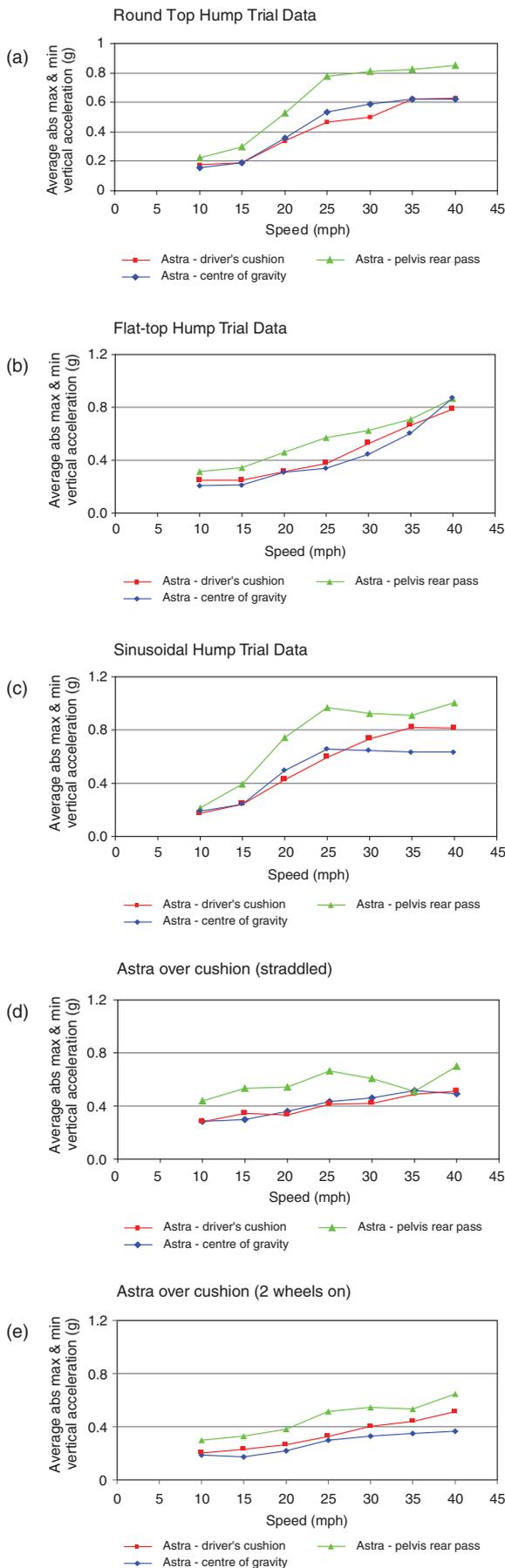
Vehicle	Total toe at:						
	Start of testing	End of measurement runs over humps	Reset	End of all runs over cushion	Reset	End of durability runs over humps	Manufacturer’s tolerances
Car <sup>1</sup>	0° 38’	0° 42’	0° 19’	0° 13’	0° 13’	0° 13’	0° 19’ ± 20’
Taxi	2.1mm/m	2.8mm/m	2.0mm/m	3.0mm/m	2.0mm/m	1.8mm/m	1.5 to 3.0mm/m
Ambulance	0° 15’	-0° 03’	0° 15’	<b>0° 43’</b>	0° 14’	<b>1° 23’</b>	-0° 03’ to 0° 27’
Bus <sup>1</sup>	0.0mm/m	0.2mm/m	0.0mm/m	0.0mm/m	0.0mm/m	0.2mm/m	0.0 to 5.3mm/m
Minibus	0° 10’	<b>0° 46’</b>	0° 08’	<b>-0° 24’</b>	0° 12’	0° 12’	0° 10’ ± 10’

<sup>1</sup> Although the toe was on the limit of the manufacturer’s specification, it only moved by very small amounts. For the bus, it remained within the allowed tolerances.

<sup>2</sup> Figures in bold indicate values significantly outside the manufacturer’s specification.



**Figure 10** Traces produced at centre of gravity of car passing over the flat top hump



**Figure 11** Average of absolute values of maximum and minimum acceleration against speed for the car

Figures 11a-c suggest that for the round top, flat top and sinusoidal humps, the vertical acceleration values experienced by a rear seat passenger in the Astra would be similar to those for the driver, except in the mid range of speeds from 20 to 30mph when the passenger values would be higher. The sinusoidal hump gave the highest acceleration values, but these were only slightly greater than for the round top hump.

Figures 11d-e suggest that for the speed cushion, whether straddled or not, vertical acceleration values remain fairly low for both driver and passenger, although again values for the passenger are higher in the mid range of speeds.

### Subjective comfort ratings

Subjective ratings of comfort by the driver and a passenger in the rear seat are given in Tables 7a (humps) and 7b (speed cushions) at speeds of 15, 20 and 25mph for all vehicles.

Ratings for the car were generally similar for driver and passenger. The maximum was 4 (uncomfortable), for the sinusoidal hump at 25mph, compared with 2 (slightly uncomfortable) over the round top and flat top humps and 3 for the speed cushion with 2 wheels on, at the same speed. Straddling the speed cushion was fairly comfortable at all speeds.

Clearly the results obtained are based on too small a sample to be robust, but they are indicative of the likely effects on vehicle occupants and they demonstrate a fairly good correlation with average absolute maximum and minimum values of vertical acceleration (see Figure 12).

### 3.3.2 Taxi

#### Vehicle condition and static testing

The London taxi was an LTI TX1, typical of those used in the metropolitan area. This model is believed to comprise about 20% of the fleet. The vehicle had a Y registration number (2000/2001) and had 23,745 miles on its odometer prior to testing.

Following the tests, the visual inspections did not highlight any vehicle damage. However, unlike the car, the checks did show changes in the suspension geometry. The most notable was a change of 1mm in the total toe following the measurement and durability runs over the cushion (see Table 6 in Section 3.3.1). Although this measurement remained within the manufacturer's specification, it was initially thought to be indicative of possible longer-term damage from repeatedly traversing humps. Following the measurement runs over the flat top (platform), round and sinusoidal humps, the total toe increased by 0.7mm. However, the durability runs over these humps (all at 30mph) produced a change of only – 0.2mm even though more passes were completed. There was a possibility that the changes following the measurement runs may have been caused by the passes at speeds above 30mph. Further investigation of the changes was therefore undertaken (described in Section 3.4.4).

Following the tests, there was no significant change in the static spring rates and no significant deterioration in the damper carding or in the damping performance, as

**Table 7a Summary of subjective appraisals for driver / rear passenger over round top, sinusoidal and flat top humps on a scale from 0 (comfortable) to 6 (uncomfortable)**

Vehicle	Round top			Sinusoidal			Flat top		
	15mph	20mph	25mph	15mph	20mph	25mph	15mph	20mph	25mph
Car	1 / 1	1 / 1	2 / 2	1 / 1	2 / 2	4 / 4	1 / 1	1 / 1	1 / 2
Taxi	1 / 3	2 / 5	3 / 6+	2 / 3	4 / 6+	4 / 6+	1 / 4	3 / 6	4 / 6+
Ambulance	1 / 2	3 / 4	2 / 6	1 / 2	2 / 3	3 / 5	2 / 3	2 / 4	2 / 4
Bus	0 / 0	2 / 2	3 / 5	2 / 1	3 / 2	5 / 7	2 / 1	3 / 3	5 / 6
Minibus	1 / 1	2 / 1	3 / 2	2 / 1	3 / 2	4 / 3	1 / 1	3 / 2	2 / 3

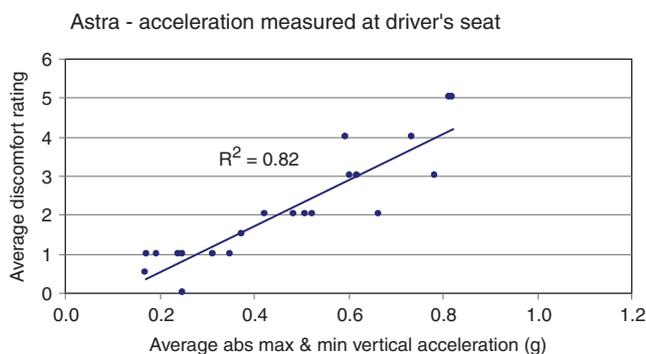
**Table 7b Summary of subjective appraisals for driver / rear passenger over speed cushion (straddled and non-straddled) on a scale from 0 (comfortable) to 6 (uncomfortable)**

Vehicle	Straddled			Two-wheels on <sup>1</sup>		
	15mph	20mph	25mph	15mph	20mph	25mph
Car	2 / 2	1 / 1	1 / 1	2 / 3	2 / 2	2 / 3
Taxi	0 / 4	0 / 4	1 / 5	1 / 4	1 / 3	1 / 4
Ambulance	0 / 1	0 / 0	0 / 0	2 / 3	2 / 2	3 / 2
Bus	0 / 0	0 / 0	0 / 0	2 / 3 (2)	2 / 2 (2)	3 / 2 (4)
Minibus	0 / 0	0 / 0	0 / 0	3 / 1	2 / 1	2 / 1

<sup>1</sup> The runs with two wheels on were with the right side of the vehicle on the hump. Ratings were for the passenger seated on the left hand side with those for the passenger seated on the right hand side in brackets where applicable.

*Subjective comfort ratings*

Subjective comfort ratings over the humps at 15, 20 and 25mph are given in Tables 7a and 7b. The driver was reasonably comfortable, though less so than in the car. In the rear of the taxi, however, the subjective rating of comfort was scored as intolerable over the round top and sinusoidal humps at a speed of 25mph, in line with the accelerations shown in Figure 13. Although the scale was intended to be from 0 to 6, values of 10 or more were suggested. Even straddling the cushion scored 5 (between uncomfortable and very uncomfortable) at 20mph. The problem was deemed to be due to the lack of suspension travel before the bump stops (i.e. rubber bumpers on the chassis that limit the suspension travel) were contacted, which transmitted very high vertical accelerations through to the rear seat which is situated directly above the rear suspension. The taxi tested had leaf spring suspension whereas the latest models are believed to have coil springs.



**Figure 12** Average discomfort rating for car driver and passenger plotted against average of absolute values of maximum and minimum acceleration

evidenced by the damper ratios. Overall, the comparison of the pre- and post-test static measurements showed no evidence of any suspension degradation from a total of 600 runs over the road humps.

*Vertical acceleration*

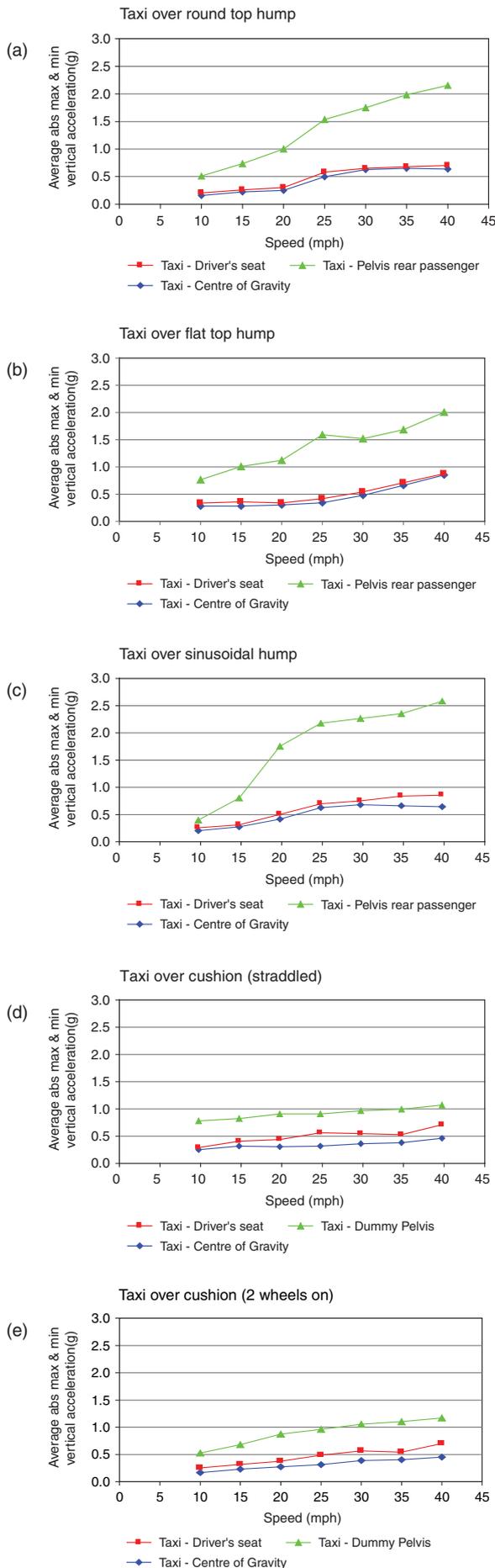
Plots of vertical acceleration for the taxi over the various humps are shown in Figures 13a-e. Most noteworthy is the very high acceleration experienced by the rear seat passenger at 15mph and above over the round top, flat top and sinusoidal humps. The acceleration for the driver at the corresponding speed was much lower.

**3.3.3 Ambulance**

*Vehicle condition and static testing*

The ambulance tested was a Ford Transit emergency response vehicle with air rear suspension. The vehicle was in new condition as it is normally used in shows. It was equipped with a stretcher, but not with resuscitation equipment. The instrumented dummy was seated in the rear crew seat, since the biomechanical model and the lumbar instrumentation are for a seated position. A second non-instrumented dummy was placed on the stretcher to make the loading more realistic.

The visual inspections did not highlight any major vehicle damage. However, the suspension geometry checks showed slight changes following the dynamic testing. The measurement runs over the round top, sinusoidal and flat top humps produced a change in the total toe of -0°18' (to -0°03'), putting it at the limit of the manufacturer's tolerances of -0°03' to 0°27' (see Table 6 in Section 3.3.1). The suspension geometry was then reset. Following the measurement and durability runs over the speed cushion, the total toe had increased by +0°28' (to 0°43'), putting it out of specification by 0°16'. The suspension geometry was again reset. Following the durability runs over the round top, sinusoidal and flat top humps, there was a change of +1°09' in the total toe (to 1°23'), putting it outside the manufacturer's tolerance range of -0°03' to 0°27' by 0°56'.



**Figure 13** Average of absolute values of maximum and minimum acceleration against speed for the taxi

The comparison of the pre- and post-test damper carding and static spring rates showed no sign of degradation from a total of 600 passes over the road humps. However, the comparison of the pre- and post-test vehicle drop test results did highlight a large reduction in the front suspension damping ratios. As the change was not seen in the damper carding test, it could be attributed to a reduction in the whole system damping, possibly due to minute changes in the rubber bushes. This represents a normal phenomenon in what was a fairly new vehicle rather than damage or accelerated degradation to the suspension.

#### Vertical acceleration

Plots of vertical acceleration for the ambulance over the various humps are shown in Figure 14a-e. As was the case for the taxi, the rear seat passenger experienced very high accelerations at a speed of 15mph and above over the round top, flat top and sinusoidal humps. These accelerations were lower for the driver at the same speeds, but were still high at 20mph and above. The speed cushions generally had low accelerations for the driver, even at higher speeds, but slightly higher ones for the passenger, especially with two wheels on, although less than with full width humps.

#### Subjective comfort ratings

The subjective appraisals, summarised in Table 6, were broadly in line with Figure 14. Although the driver was reasonably comfortable, the rear seat occupant rated the round top and sinusoidal humps as very uncomfortable at 25mph (and intolerable at higher speeds). The effect was deemed to be due to the dynamic characteristics of the rear suspension coupled with the pitching motion induced when travelling over the humps, transmitting large vertical accelerations through to the rear-seated occupant.

The speed cushion was reasonably comfortable for driver and passenger at speeds of up to 20mph.

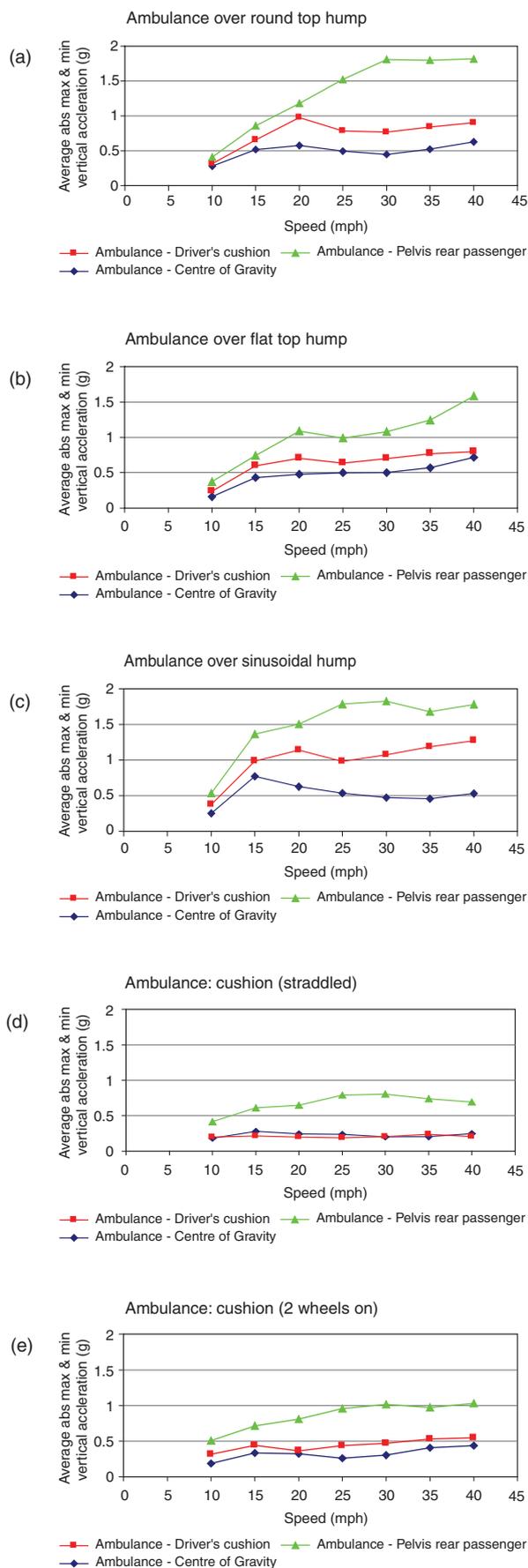
The data confirm the benefit of speed cushions in preference to full width humps on strategic routes used by emergency vehicles.

#### 3.3.4 Single deck bus

##### Vehicle condition and static testing

The bus was an 11.8m low floor single deck bus with a Volvo chassis and a Robert Wright body, with a full air suspension system, and was Disability Discrimination Act compliant with respect to the features relevant to the study. (The differences related to the interior of the cabin only, for example the number of steps, aisle width, handholds etc, and did not affect the suspension or ride). It had done 15,247 miles prior to the testing.

Durability runs were undertaken at 25mph. The visual inspections did not highlight any major vehicle damage and the suspension geometry checks showed only minor changes. The total toe was initially at the limit of the manufacturer's tolerance (Table 6) but moved back inside the manufacturer's tolerances following the measurement and durability runs.



**Figure 14** Average of absolute values of maximum and minimum acceleration against speed for the ambulance

The comparison of the pre- and post- drop test results showed no signs of suspension degradation from a total of 981 passes over the road humps.

Very little movement of the wheelchair was detected – less than 5mm longitudinal and less than 6mm latitudinal displacement in either direction.

#### Vertical acceleration

When considering the plots of vertical acceleration over the humps shown in Figure 15, it is worth noting that bus companies are recommended to advise their drivers to cross humps at 15mph. Over the round top and sinusoidal humps, the rear seat passenger experienced high accelerations at 15mph and above. These accelerations were lower for the driver, but were still high at 20mph. By contrast, over the flat top hump, the driver was less comfortable than the passenger at 20mph.

As might be expected, with the bus straddling the speed cushion, vertical accelerations for the driver remained fairly low and were only slightly higher with 2 wheels on it (Figure 15). Accelerations for the passenger were higher than for the driver at 25mph, particularly with two wheels on.

#### Subjective comfort ratings

The driver and two passengers undertook the subjective appraisals. All three occupants found the passes over the humps to be fairly uncomfortable at 25mph over the flat top, round top and sinusoidal humps (Table 7a). Both the driver and the passenger in the rearmost seat (the position deemed to give the worst subjective rating) were affected by the overhang of the bus. This, coupled with the pitching motion of the vehicle, amplified the accelerations experienced by the rear-seated occupants. There was a noticeable deterioration in driver comfort above 20mph – the driver's air seat was not considered to react quickly enough. This could be a concern for drivers who regularly drive on roads with humps, possibly traversing up to 100 humps a day with a schedule to keep to.

When the speed cushion was straddled, both driver and passengers gave a 'comfortable' rating even at 25mph (Table 7b). When the speed cushion was traversed with 2 wheels on the right hand side of the hump, comfort for the passenger was affected by which side of the bus s/he was seated in. At 25mph, a passenger seated on the right was uncomfortable, whereas a passenger seated on the left was only slightly uncomfortable.

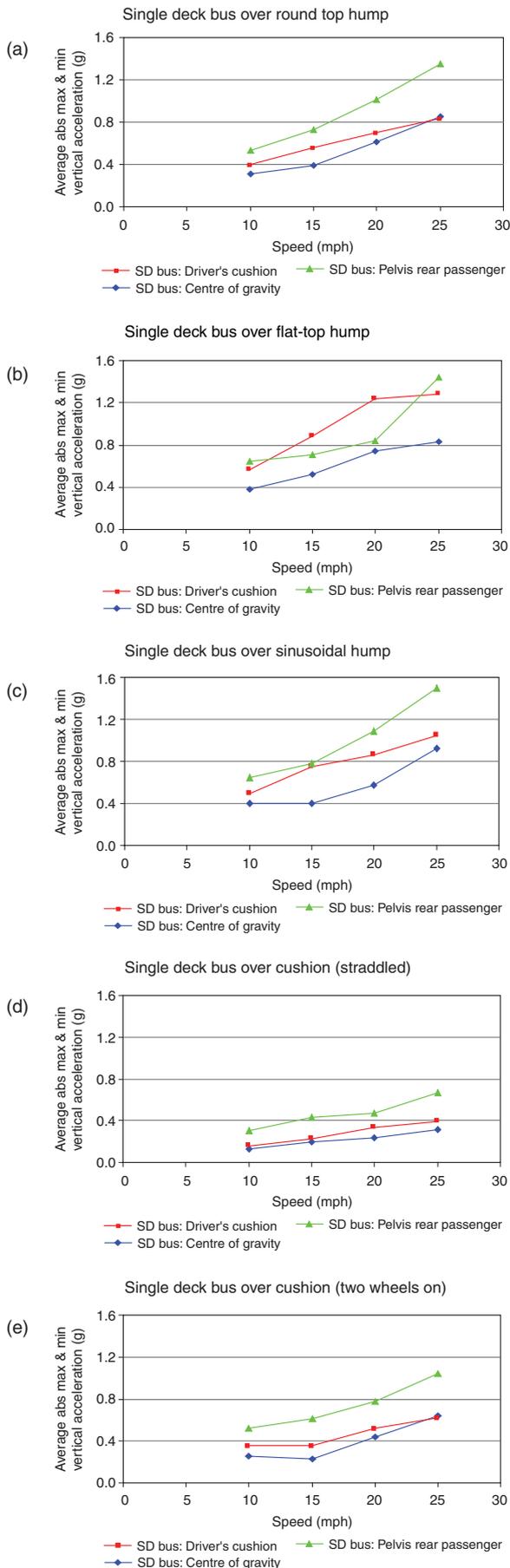
The data confirm the benefit of speed cushions in preference to full width humps on bus routes.

### 3.3.5 Minibus

#### Vehicle condition and static testing

The minibus was a Y registration (2000/2001) Vauxhall Movano seating 12, and capable of carrying wheelchair passengers. It had done 2,871 miles.

Durability runs were undertaken at a speed of 25mph. The visual inspections did not highlight any major vehicle damage. However, the checks did show changes in geometry following passes over the humps (see Table 6 in Section 3.3.1). The most notable was the change of +0°36'



**Figure 15** Average of absolute values of maximum and minimum acceleration against speed for the single deck bus

in the total front toe (to  $0^{\circ} 46'$ ) following the measurement runs over the round top, sinusoidal and flat top humps. This put the total toe outside the manufacturer's tolerances of  $0^{\circ}10' \pm 10'$  by  $0^{\circ}26'$ . The suspension geometry was reset. Following the measurement and durability runs over the speed cushion, the total toe changed by  $-0^{\circ}32'$  (to  $-0^{\circ}24'$ ), putting it outside the manufacturer's tolerances by  $0^{\circ}24'$ . The suspension geometry was again reset. There was no change in the total toe following the durability runs over the full width humps.

The post-test static measurements showed no signs of suspension degradation from a total of 600 runs over the road humps compared with the pre-test results.

#### Vertical acceleration

Plots of vertical acceleration over the various humps are shown in Figures 16a-e. Accelerations were fairly high for both driver and rear seat passenger at speeds of 25mph and above, with the effect on the driver similar to that on the passenger. Results over the round top, flat top and sinusoidal humps and the speed cushion with 2 wheels on were similar, although accelerations for the driver were lower than for the passenger at higher speeds over the flat top hump. Straddling the speed cushion resulted in fairly low accelerations for both driver and passenger.

#### Subjective comfort ratings

Subjective appraisals (Tables 7a and 7b) suggested little difference between the driver and the passenger. None of the humps was rated at more than moderately uncomfortable at speeds up to 25mph.

### 3.4 Summary and further testing

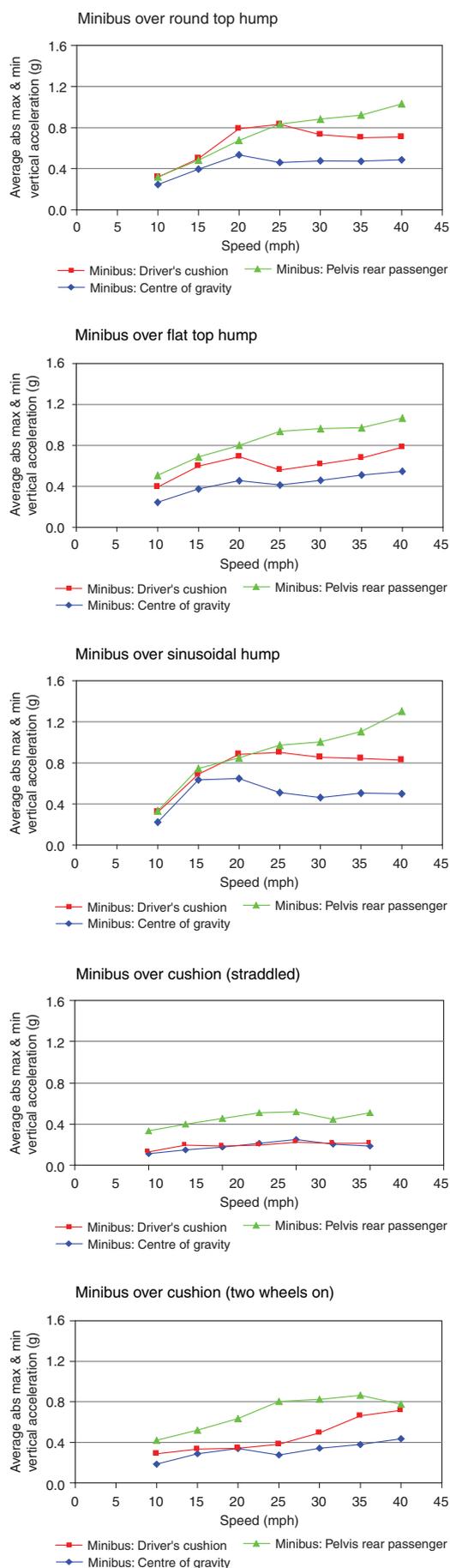
#### 3.4.1 Vehicle

The initial findings for the vehicle were as follows:

- Visual inspections revealed no substantial vehicle damage for any of the vehicles during more than 600 passes over the humps. However, suspension geometry checks showed small changes in toe following the passes over the humps and these changes were outside the manufacturers' tolerances for the taxi, the ambulance and the minibus (Table 6).
- The ambulance was the only vehicle to show a large reduction in the front suspension damping ratios following the tests. This change was attributed to a reduction in the whole system damping, considered normal in what was a fairly new vehicle.

#### 3.4.2 Vehicle occupants

- Reported discomfort ratings were found to be strongly correlated with measured peak vertical accelerations. These subjective ratings were based on one driver and one or more passengers. Although this is clearly too small a sample to provide robust results, their correlation with the accelerations suggests they are indicative of the likely effects on vehicle occupants.



**Figure 16** Average of absolute values of maximum and minimum acceleration against speed for the minibus

- The peak vertical acceleration was below 0.7g for the driver in the car and the taxi over the round top, flat top and sinusoidal humps at 20mph and in the ambulance and minibus at 15mph, broadly corresponding to subjective ratings in the Millbrook testing of 'slightly uncomfortable' to 'uncomfortable'. The value for the bus driver was slightly above 0.7g over the flat top and sinusoidal humps at 15mph, but below 0.7g for the round top hump.
- The peak vertical accelerations for the rear seat passenger were similar to the values for the driver in the car at 20mph and the minibus and bus at 15mph over the round top, flat top and sinusoidal humps. The peak vertical acceleration over these humps for the passenger in the rear of the taxi was much greater (and reported discomfort was also substantially higher) than for the driver, even at 15mph. This may be due to the leaf spring suspension in the taxi tested. The latest models are believed to have coil springs. In the ambulance, the peak acceleration was slightly greater for the passenger in the rear crew seat than for the driver at 15mph, with a much greater differential at higher speeds. Of the full width humps, the flat top hump was better than either the round top or the sinusoidal for the ambulance passenger.
- The peak vertical acceleration over the cushion was well below 0.7g for both driver and rear seat passenger in the car at 20mph and the bus and minibus at 15mph, whether the cushion was straddled or crossed with two wheels on. For the rear passenger in the taxi and the ambulance, the peak vertical acceleration was higher than for the driver, but still less than for full width humps. The passenger in the ambulance experienced little discomfort when straddling the cushion.

It was concluded that the levels of discomfort associated with measured peak vertical acceleration were generally acceptable if the humps were traversed at the appropriate (intended) speeds i.e. not exceeding 15 to 20mph. Although passengers in the rear of taxis suffer considerably more discomfort than drivers, experienced taxi drivers are well aware of this and tend to approach road humps at very low speeds. Ambulance drivers will act in accordance with the situation.

### 3.4.3 Significance of changes in toe angle

From the preceding sections, it is evident that with the exception of the ambulance, the only changes found were in the toe angle. The relatively small changes seen would not give any noticeable effect to the driver in terms of the steering feel or handling, even where the tolerance band was exceeded.

Accelerated tyre wear is a possible effect of toe angle exceeding the tolerance, but it is considered that it would become noticeable to the vehicle driver only at greater deviations from specification than those seen during the tests. Since tyres are inspected at the annual MOT test, there is little chance of any defective condition developing that would go unnoticed. Vehicles require periodic adjustment of toe angle during correct maintenance, since driving over normal road input features can give gradual

toe angle change. That is why tyre centres and garages have the necessary equipment and have routinely carried out such checks during tyre changes for many decades, not just since humps have become common.

### 3.4.4 Further testing

Further testing was undertaken at Millbrook in order to:

- 1 Determine the forces generated in various other normal driving situations, such as a sharp bend, for comparison purposes .
- 2 Investigate the reasons for the changes in toe angle noted above (Section 3.4.3) .
- 3 Undertake further durability testing for the taxi, ambulance and minibus.

The three possible vehicles for (2) were those that, following the hump traversals described above, showed changes in toe that were outside the manufacturer’s specifications and for which further durability testing was to be undertaken i.e. the taxi, the ambulance and the minibus. The taxi was selected as this is the simplest vehicle mechanically and it is also smaller than the other two. The taxi was also used for (1).

### Comparison of forces generated when traversing humps compared with those in other normal driving situations

The taxi was tested over the various humps at 30mph in order to determine which gave the highest tie rod forces (Figure 17). It was found that straddling the cushion gave higher tie rod loads than two wheels on the cushion or the other humps (Table 8) and this manoeuvre was therefore selected for the investigation of the changes in toe angle.

Other driving manoeuvres, though occurring infrequently, such as potholes, heavy braking, parking against a kerb produced tie rod loads that were similar to, or higher than, traversing humps.

### Further investigation of toe angle

The testing of the effect of repeated driving over the speed cushion was undertaken on a test rig in the laboratory. The maximum forces generated in the tie rod from straddling the cushion were replicated using servo-hydraulic actuators at the same rate of application. The simulation tests were equivalent to 3000 passes over the cushion. Suspension geometry checks were undertaken after every 600 passes, without re-setting the toe. The changes in front axle toe during these tests are shown in Figure 18. The toe

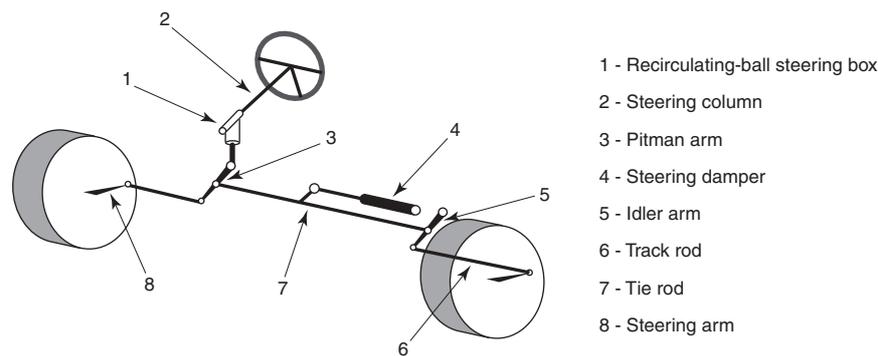
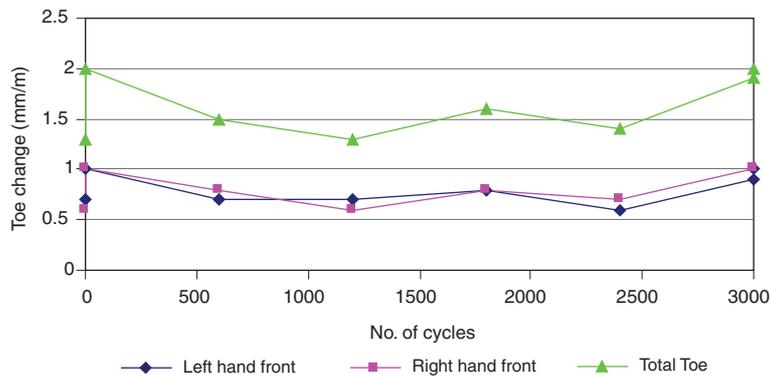


Figure 17 Steering assembly on taxi

Table 8 Taxi steering tie rod maximum loads

Manoeuvre	Tie rod max loads (N) <sup>1</sup>	
	Left	Right
Round top	1120	1545
Sinusoidal	882	1270
Flat top	996	1516
Cushion straddled	-2516	-3079
Cushion 2 (LH) wheels on	-2050	1932
Cornering RH lock (steady state, 33m radius, 33km/h)	498	-704
Heavy braking at 15mph	605	866
Heavy braking at 20mph	857	1122
Potholes at 10mph	1242	1973
Potholes at 15mph	1610	2908
Mount kerb during parking	-2236	4188
Jacking against kerb (steering wheel moved in both directions)	-2761	-6584
Rough road driving (Millbrook Special Surface)	-1590	-2851

<sup>1</sup> Positive numbers indicate tension, negative compression.



**Figure 18** Toe change (mm/m) on taxi during hydraulic rig simulation

did go out of specification (range from 1.5 to 3.0mm/m). However it did not continue to get worse, but drifted in and out of specification, with a total change of only  $\frac{3}{4}$ mm. It is important to note that only the track rod loads were replicated, whereas dynamically, the steering geometry may be affected by forces on other components when traversing humps. The geometry changes produced are almost certainly due to deformation in the compliant elements in the system such as suspension arm bushes, control arm bushes, steering rack mounting, track rod ball joints etc, and it is highly probable that the changes in toe are due to an accumulation of very small deformation in each element, rather than in one single element.

The toe-in was more affected when the vehicle traversed the speed cushion with 2 wheels on than when straddling it. This suggests that forces on other structures such as the wishbones are involved. This may in part be a consequence of the steering system used on the taxi.

#### *Additional durability testing*

Additional durability testing of the minibus, the ambulance and the taxi was undertaken to establish the speeds deemed to be sufficiently low to avoid substantial changes in toe. The minibus and taxi were tested over the speed cushion and the ambulance over all hump types.

The total toe on the taxi did not change after straddling the cushion at 25mph or at 30mph. However, it did change after the test at 25mph with two wheels on, to outside the top end of the tolerance band. When the test was repeated at 20mph, the toe again went out of specification, but this time below the tolerance band. This characteristic is consistent with the findings above i.e. that the toe changes were due to compliance within the suspension system as opposed to a systematic effect. After resetting, the test with two wheels on the cushion at 15mph showed no toe-in change.

The fact that the taxi toe-in changed during the test with two wheels on the cushion, but did not change when straddling it, goes against the higher loads recorded when straddling. This, in turn, could indicate that the loads were affecting the system by some other means, such as via the suspension lower arm.

For the ambulance, there was no change in toe after the tests over the round top, flat top and sinusoidal humps at either 20mph or 25mph. The test with two wheels on the

cushion at 25mph also gave no change in toe. No tests were conducted straddling the cushion because the front wheels completely cleared the hump.

The tests on the minibus showed that the toe did not change after the 20mph or the 25mph tests either straddling the cushion or with two wheels on.

In summary, the speeds at which vehicles traversed the humps without substantial changes in toe were:

Minibus	40mph over the round top, flat top and sinusoidal humps. 25mph over the cushion (straddling and 2 wheels on).
Ambulance	25mph over all hump types.
Taxi	40mph over the round top, flat top and sinusoidal humps. 30mph straddling the cushion. 15mph with 2 wheels on the cushion.

The corresponding speeds for the car and the bus were 40mph over all hump types.

## **4 HVE modelling**

### **4.1 HVE software package**

HVE (Human-Vehicle-Environment) is a sophisticated software package that combines several different simulation models for the analysis of vehicle and occupant dynamics. It can be used by vehicle design engineers and safety researchers to perform dynamic simulation studies such as occupant kinematics, vehicle handling and response and crashworthiness, and to examine compliance issues such as brake system effectiveness. HVE is particularly suited to studies examining the dynamic response of a vehicle to physical road features.

Single vehicle analysis models such as HOVSM (Highway Object Vehicle Simulation Model) were originally developed to examine the interaction of vehicles with highways and highway structures. The SIMON (SIMulation MODEL Non-linear) physics model now included in the HVE software has significantly extended the analytical capabilities of HOVSM, allowing a wide range of vehicle parameters to be tested and related to vehicle performance.

HVE simulations are conducted within a three dimensional environment, allowing three dimensional road surfaces to be negotiated by simulation vehicles. The three dimensional response of the simulation vehicle to the shape of road surface is modelled during the simulation, providing detailed data describing the dynamic response of the vehicle.

#### 4.2 Methodology

Road hump design requires a balance between the speed reducing effect of the hump and the level of comfort afforded to vehicle occupants as they travel over the feature. Previous research into the severity of road humps has used vertical acceleration as an indicator of hump severity, and, therefore, comparisons between the physical tests at Millbrook (Section 3) and the simulation, or ‘virtual’ tests, focused on matching the respective vertical acceleration profiles.

HVE was used to:

- Create vehicle models with specified characteristics.
- Create the three dimensional road geometry for each hump.
- Simulate the test vehicles being driven over each hump at different speeds.
- Position virtual accelerometers within the test vehicles to monitor tri-axial accelerations at the vehicle’s centre of gravity and occupant positions.
- Add ‘virtual’ occupants of suitable weight and height
- Study the effect of occupant positioning inside the vehicle.

The ‘virtual’ HVE test vehicles were built using the dimensions, suspension, mass and other characteristics as measured by Millbrook wherever possible. (The suspension stiffness of the single deck bus could not be physically measured as its air suspension systems on both the front and rear axles continually adjust the air pressure to keep a constant ride height. In this case, design suspension stiffness data was obtained from the manufacturer. It was not

possible to measure, or source, any suspension stiffness information for the rear axle of the ambulance, which also utilises an air suspension system.)

Vehicle inertia properties were calculated from the measured dimensions. Tyres were selected with the same size/aspect ratio as those fitted to the test vehicle, or were as close as possible. The measured damping rates were adopted for the shock absorber parameter.

In assessing the consistency between the results of the practical testing and the simulation, a number of key parameters were examined, these being:

- vertical acceleration at the centre of gravity (CoG);
- pitch angle and pitch rate;
- wheel vertical displacement.

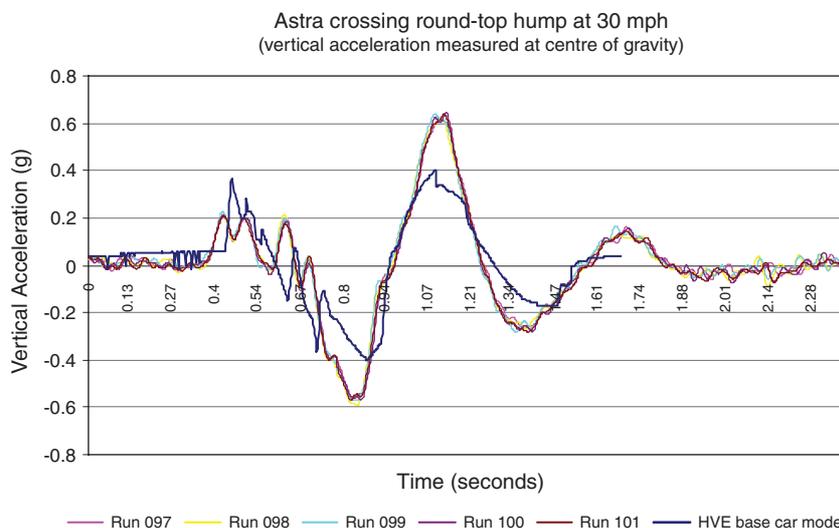
#### 4.3 Results

##### 4.3.1 Comparison of initial simulation results with physical test data

The initial comparison of the simulation results with physical test data was conducted using the ‘virtual’ car travelling over the round top hump at 30mph. The set up of the vehicle in this case used the vehicle geometry and suspension parameters as measured by Millbrook.

Measurements obtained from the physical tests were observed to show a high level of consistency and repeatability, as illustrated by the five vertical acceleration profiles recorded for the car travelling over the round top hump at 30mph, Figure 19. However, when the preliminary simulation was compared with the Millbrook test data, there was some variation. Whereas the pattern of CoG vertical acceleration and pitch angle/rate simulation data was very consistent with that of the test data, the peak levels of these variables calculated by SIMON were found to be lower than the physical test data. Figure 19 shows this relationship for CoG vertical acceleration.

Of the key parameters assessed, the results for wheel vertical displacement showed the greatest consistency between the physical test data and the simulation data.



**Figure 19** Comparison of physical and initial simulation test results for the CoG vertical acceleration of the car

### 4.3.2 Sensitivity testing

Sensitivity analyses of key input variables such as suspension characteristics (springs and damping) and accelerometer mounting positions were undertaken to establish a 'best fit' between the simulation and physical test results. Sensitivity tests for the car travelling at 30mph over the round top hump were carried out to examine the effects of variations in several key simulation vehicle parameters, as follows:

- Spring rate.
- Damping rate.
- Damping friction.
- Pitch inertia.

The tests showed that, of the above vehicle properties, the spring rate and damping rate had the greatest effect on the simulation results. Increasing the spring rate provided increased peaks in each of the simulation profiles and improved the correlation between the virtual test data and the physical data. It was found that relatively small variations in spring rate could account for variations between the physical and simulation data that other parameters could not.

Reduced damping rates also provided increased peaks in vertical acceleration, and generally improved the correlation between the virtual test data and the physical data.

Variations in the pitch inertia caused a slight increase in the peak levels of pitch angle and pitch rate.

In order to assess the sensitivity of the CoG accelerometer location in the physical test car, i.e. the Vauxhall Astra, a number of virtual accelerometers were positioned within the simulation vehicle. These accelerometers were positioned at distances of up to 30cm from the simulation vehicle's centre of gravity in the longitudinal and vertical directions. These tests examined variations in the simulation results in the event that the CoG sensor was not positioned exactly at the centre of gravity of the test vehicle. It was found that the

accelerometer positions examined had no significant effect on the simulation results.

No sensitivity analyses were performed on tyre variables.

### 4.3.3 'Best fit' results

#### Car

A 'best fit' simulation for the car travelling over the round top hump at 30mph is shown in Figure 20. Relatively straightforward manipulation of the vehicle's properties as described in Section 4.3.2 provided a good correlation between the simulation and physical test results. These modifications were adopted for the car at other speeds and over other hump types and were found to provide good consistency between the simulation and physical test results.

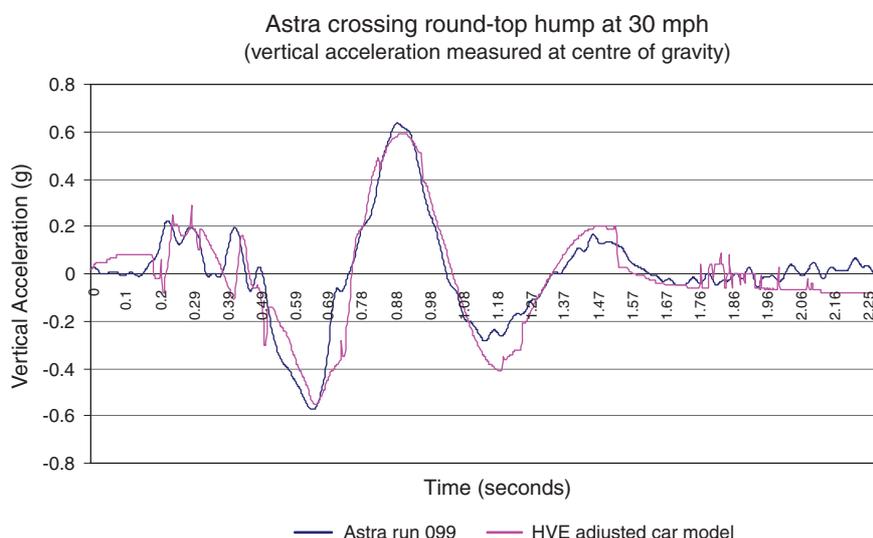
#### Taxi

Initial simulation results (based on measured values) for the taxi provided relatively low peaks of vertical acceleration and pitch rotation. Further simulations were therefore carried out using the same 'best fit' modifications as those adopted for the car. These modifications to the taxi model provided results that showed good consistency between the physical and simulation test results. Figure 21 shows the vertical displacement of the front left wheel of the taxi (rather than the vertical acceleration at the centre of gravity) crossing the flat top hump at 30mph.

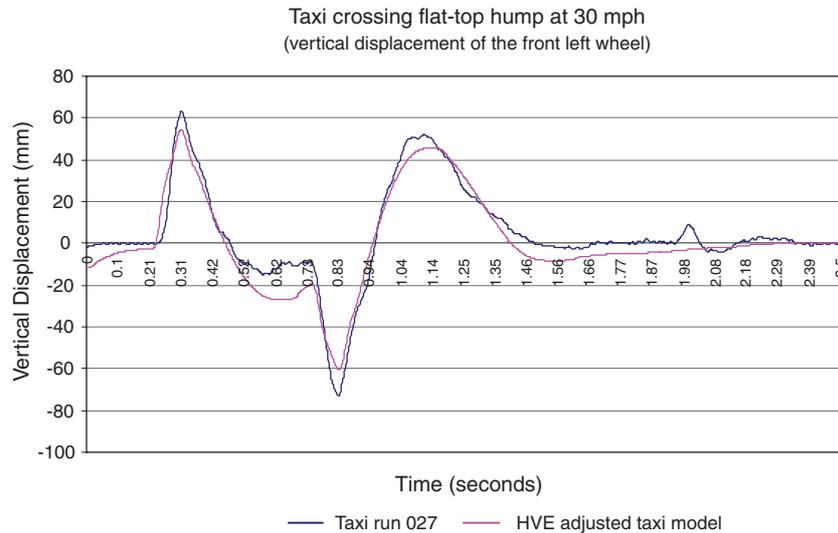
#### Ambulance

Initial simulation results of the ambulance were calculated using both a solid suspension and an independent rear suspension, due to there being no air suspension model within HVE or SIMON. These tests demonstrated there was little or no difference between these suspension models at the speeds tested. For the purpose of further simulations, an independent rear suspension system was selected.

It was found that by adopting the measured suspension properties on the front axle, increasing the spring rates and



**Figure 20** Comparison of physical and 'best fit' simulation test results for the CoG vertical acceleration of the car



**Figure 21** Comparison of physical and ‘best fit’ simulation test data for the vertical displacement of front left wheel of the taxi

decreasing the rear axle damping rates, the vehicle model provided good consistency between the physical data and the simulation test results. Figure 22 shows the pitch angle for the ambulance crossing the speed cushion with two wheels on at 30mph.

#### Single deck bus

Initial simulations for the single deck bus were carried out using an independent suspension system and the same ‘best fit’ modifications as those adopted for the car analyses, i.e. increasing spring rates and decreasing damping rates. The simulated vertical accelerations that were observed based on these modifications were well below the peak levels shown in the physical test data.

Extensive variations of the spring and damping rates were examined for both axles, separately and in tandem. Although some of these combinations improved the correlation between the physical and test data, the alterations also affected the pattern of the simulation data to such an

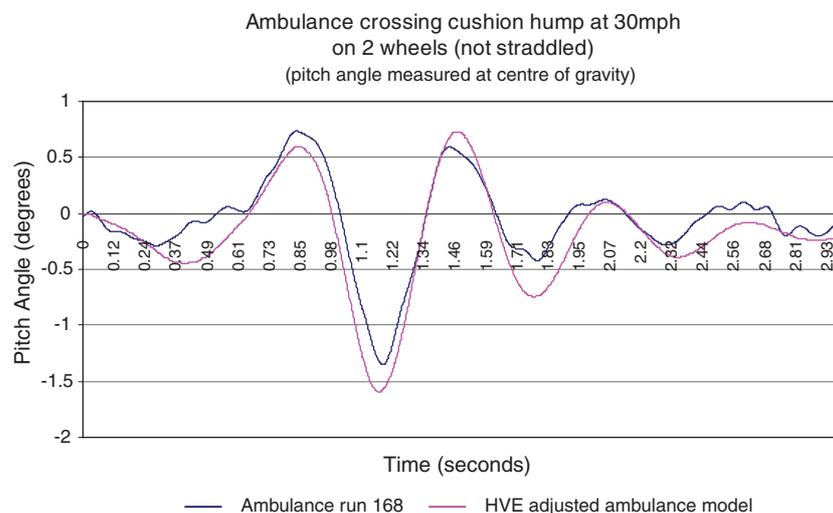
extent that it became less consistent with the physical test data in the period after the vehicle travelled over the hump, i.e. during the phase in which the vehicle movement settled back to normal after traversing the hump.

Additional sensitivity analyses were conducted to examine the effect of the inertial properties of the bus. These simulations showed no significant effect during the period of highest vertical accelerations, i.e. before the vehicle had fully cleared the hump. However, some effect was observed as the vehicle was settling after travelling over the hump. As expected, decreasing the pitch inertia resulted in higher peak vertical acceleration levels during this period.

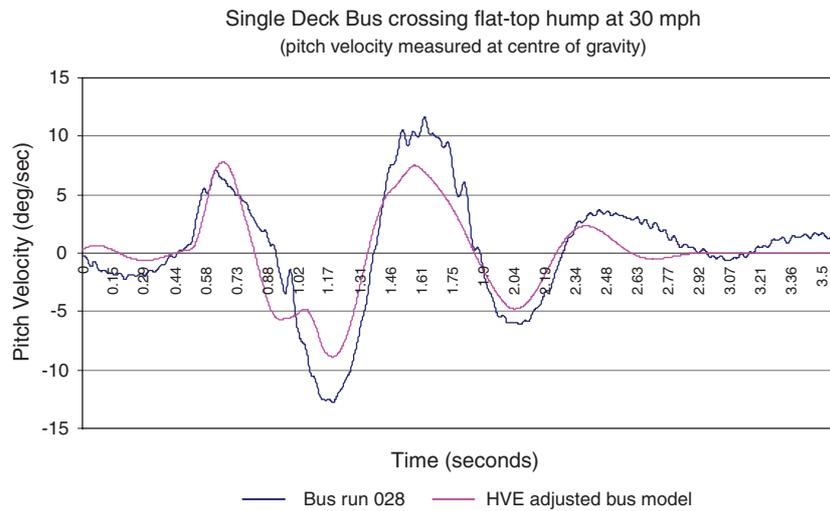
Figure 23 shows the 'best fit' pitch velocity for the bus over the flat top hump at 30mph.

#### Minibus

The initial testing for the minibus followed a similar approach to that adopted for the ambulance. The



**Figure 22** Comparison of physical and ‘best fit’ simulation test data for the pitch angle of the ambulance



**Figure 23** Comparison of physical with ‘best fit’ simulation and test data for the pitch velocity of the single deck bus

simulation results from these modifications were not generally consistent with the physical test data. Further sensitivity analyses identified the need for a significant reduction in rear damping. However, this modification caused prolonged bounce of the rear suspension after travel over the hump, as shown in Figure 24 for the minibus crossing the sinusoidal hump at 20mph and Figure 25 for the minibus crossing the round top hump at 30mph.

The relationship between the physical and simulation test data in each of these cases was observed to be closer in the period that the vehicle was in contact with the humps than during the post-hump damping.

#### 4.4 Summary of HVE modelling

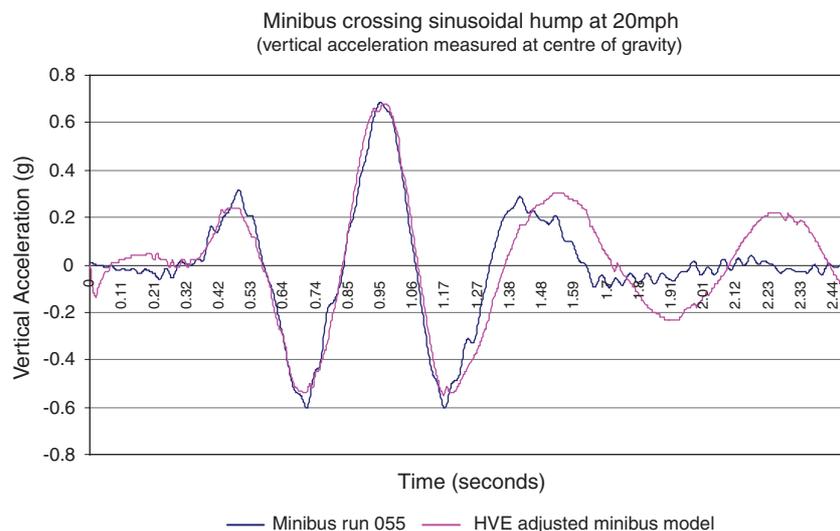
It was important to attempt to maximise the consistency of the physical and simulation data in the vehicle/hump ‘contact’ period since it is during this time that the most significant accelerations are experienced by both the vehicles and occupants. Therefore the ‘best fit’ for all vehicles was selected as being most consistent with the test

data during the period in which the vehicle was travelling over (i.e. in contact with) the road hump.

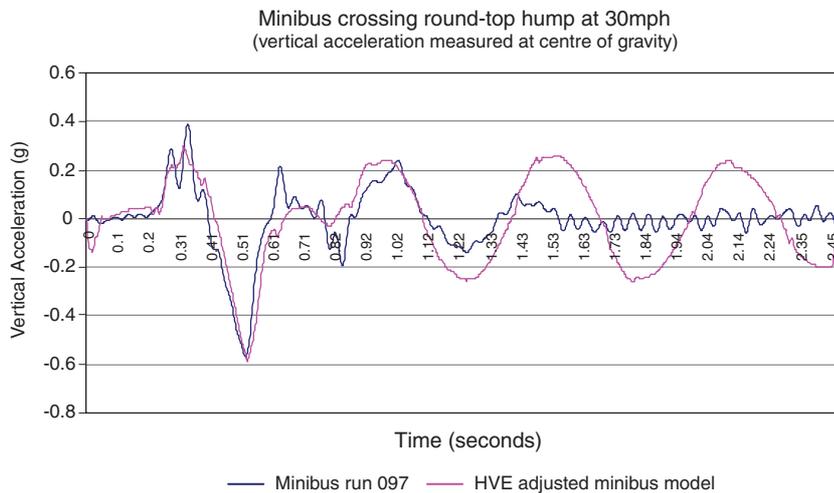
During the contact phase between vehicles and the road humps, the ‘best fit’ simulation data was then highly consistent with the physical test data in terms of the form, or pattern, of the data - which was characteristically different for each type of hump and vehicle.

There was more discrepancy in the period after the vehicles had travelled over the humps. This effect was particularly evident for the minibus; this is explained by the changes in the suspension parameters that were required to develop the ‘best fit’ simulation for the period in which the vehicles were in contact with the humps. By reducing the effective damping at the rear of the vehicle, a high degree of suspension bounce occurred after the minibus travelled over the humps (Figures 24 and 25).

In general, the car, taxi and ambulance provided the best fit between the physical and simulation data for each hump. The speed cushion showed the least correlation for all vehicles.



**Figure 24** Comparison of physical and ‘best fit’ simulation test data for the CoG vertical acceleration of the minibus



**Figure 25** Comparison of physical and ‘best fit’ simulation test data for the CoG vertical acceleration of the minibus

The single deck bus provided results with the least fit between the physical and simulation test data. It is considered likely that the design of this vehicle’s front and rear air suspension contributed to this.

Whilst the minibus in general provided good results during the travel over the hump phase, it did not provide good results during the post hump phase (the most likely explanation for this is discussed above).

In the absence of sensitivity analyses having been carried out on tyre variables, it is possible that the tyre characteristics and/or tyre model contributed to the variations between the physical and simulation test data, although further work would be required to address this issue.

It is not known whether the differences between the physical test data and the simulation results (using measured suspension values) are due to the methods adopted to measure the suspension properties of the vehicles, or due to the idealised suspension model within SIMON. However, regardless of the specific suspension parameters adopted for these analyses, the fundamental pattern of the simulation data, in comparison to the physical test data, showed very good consistency with the characteristic forms of the data for the key parameters examined.

#### 4.5 Investigation of other driving events

In addition to the further testing undertaken at Millbrook to investigate the reasons for toe angle changes on certain vehicles (Sections 3.4.3, 3.4.4), a series of simulation analyses using HVE was undertaken to examine the nature of the force input to vehicles during travel over road humps, using the car as an example. The results of these analyses were compared to the force input into the suspension during other driving events such as braking, cornering and travel over uneven surfaces such as potholes.

##### *Forces generated in traversing road humps*

The longitudinal and lateral forces experienced at the front wheels (at the tyre/road interface) of the car during travel over a round top hump, a flat top hump and a speed cushion were assessed at various speeds.

The lateral and longitudinal forces generated at the front wheels of the simulation vehicle during travel over the round and flat top humps were characterised by relatively low levels of longitudinal force and little if any lateral force. The levels of longitudinal force predicted by HVE for vehicles travelling over road humps were typically around 1200 Newtons (N) at 30mph and 650N at 20mph. In comparison the static vertical front tyre load for the passenger car was around 3650N. These force levels are compared below to the level of longitudinal force incurred during heavy braking and with more typical levels of braking.

Under heavy braking, relatively high levels of longitudinal force are generated between the front tyres and the road. At maximum rates of deceleration (consistent with emergency braking) longitudinal tyre loads can reach around 95% of vertical tyre load during braking (including weight transfer). This level of force is significantly greater than the level of longitudinal force generated by a vehicle travelling over a typical road hump, and greater than the static vertical load on the tyre. Under lower levels of braking, consistent with more normal driving, longitudinal tyre force can easily reach 30% of static vertical tyre load. On a typical passenger car this can mean longitudinal forces of over 1000 N on each of the front tyres during moderate levels of braking. This is broadly consistent with (if not greater than) the level of longitudinal force experienced when negotiating a road hump.

In comparison to the forces experienced during travel over full width humps, travel over the speed cushion gave similar levels of longitudinal force, whereas relatively high levels of lateral force were also generated.

At all speeds, relatively constant levels of lateral force were applied to the front tyres as the vehicle straddled the hump (with the tyres travelling over the side ramps). The peak lateral forces at the front wheels were in the order of 420 to 430N at speeds of 20mph to 30mph (these values equating to around 12% of static vertical tyre load). These forces act at the contact point between the inner portion of the tyre and the surface of the hump, and act outwards from the vehicle. The side gradient of the cushion tested was 1 in 4; higher gradients would potentially give higher levels of lateral force, whereas lower gradients would give less force.

### Forces generated when cornering

The level of lateral force typically incurred during normal cornering was also assessed using HVE. The lateral force generated at the tyre during cornering was compared to the lateral forces experienced as a vehicle travels over a speed cushion to investigate whether the lateral forces generated when a vehicle straddles a speed cushion are unusually high.

In cornering situations, lateral forces develop between the tyres and the road allowing the heading of the vehicle to change. During cornering a certain degree of weight transfer will occur causing the nearside and offside wheels to experience differing levels of vertical load, and lateral force. The lateral force will also act in different directions relative to the offside and nearside tyres.

When cornering to the right, weight transfer to the nearside will occur, thus giving the front nearside tyre higher vertical and lateral loads during cornering. The force acting on the nearside tyres will be towards the vehicle, whereas on the offside the force acting on the tyres will be away from the vehicle (similar to the effect of a cushion). Due to the weight transfer the magnitude of the force on the nearside tyres will be greater than the force on the offside tyres.

When cornering to the left, the direction of weight transfer and force direction on the nearside and offside tyres are reversed.

The direction of the force acting on the vehicle's tyres during travel over a speed cushion is only replicated during cornering by the inside tyre relative to the cornering manoeuvre. The levels of lateral force experienced by the inside tyres can be significantly less than the outside tyres (due to weight transfer).

The analysis of cornering forces examined cases for the car at 0.3, 0.2 and 0.1g lateral acceleration, these being equivalent to relatively hard cornering (for most drivers at highway operating speeds), moderate cornering and light cornering, respectively. In cornering, the loads experienced by a tyre will depend on the direction and severity of the steering manoeuvre, and the speed of the vehicle. In cornering at 0.3g lateral acceleration at around 45mph (a relatively high lateral acceleration for this speed in terms of normal driving), a lateral force equivalent to 35% of the static vertical load on the tyre can be applied to the outside front tyre (relative to the steer direction). By comparison, the inside front tyre may experience only 25% of the static vertical load as lateral force. In the case of the car tests, this would equate to 1260N (35% static load) and 900N (25% static load).

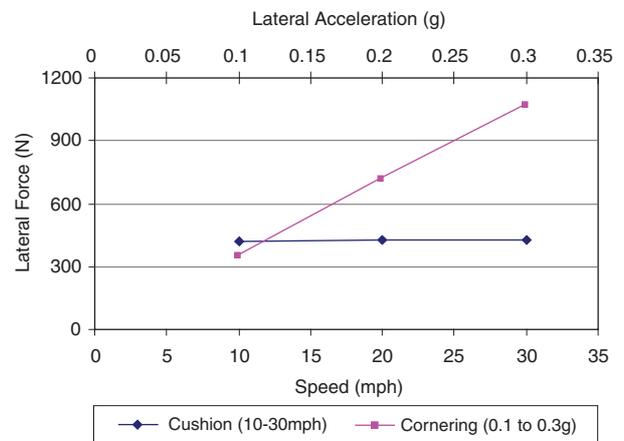
In cornering at 0.3g at a lower speed of 30mph, the difference between inner and outer tyres is reduced. However, the average lateral force on the tyres remains at around 30% of static vertical tyre load.

In cornering at 0.2g, the average lateral force on the front tyre equates to around 20% of the static vertical tyre load, or around 720N.

In cornering at 0.1g, the average lateral force on the front tyres falls to just under 10% of the static vertical tyre load, or around 360N.

In comparison to the lateral forces exerted on the tyre at the road surface when traversing the side ramp of a speed

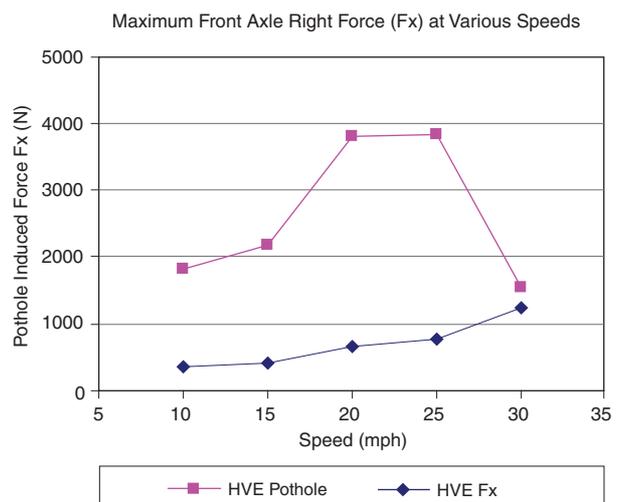
cushion, the lateral forces experienced by a vehicle during cornering are typically greater during heavy and moderate steering, and similar under light steering. The above results are summarised in Figure 26.



**Figure 26** Comparison of lateral force at front tyres during travel over a speed cushion and cornering

### Pothole

Finally, a series of simulation tests was conducted to demonstrate the levels of longitudinal force that can be generated during the travel of a vehicle over a representative pothole feature. For these tests a representative pothole of one metre long and 10 centimetres deep was constructed within the simulation environment. Figure 27 presents the relationship between longitudinal force at the tyre during travel over a road hump, and travel over the virtual pot hole.



**Figure 27** Comparison of longitudinal force at front tyre during travel over a flat top hump and a representative pothole

It can be seen that the longitudinal force at the pothole reaches a peak at around 20 to 25 mph. This relationship is defined by the dimensions of the pothole in relation to the

vehicle speed. At speeds higher than 25mph, the tyre travels over the pothole before it has had sufficient time to ‘fall’ into it too far. It can be seen that the longitudinal force generated in the pothole scenario is significantly greater than that which would be incurred during the normal travel of a vehicle over a flat top hump.

#### 4.6 Investigation of other hump profiles

HVE was also used to investigate alternative hump designs in terms of the predicted chassis accelerations. The ideal hump was assumed to be one that makes the driver slow down whilst any passengers feel no more discomfort than the driver. Vertical acceleration / discomfort for the car driver needs to be sufficient to keep mean speeds down to below the required speed, typically 20mph. For the car and taxi, this means broadly maintaining the existing relationships between speed and vertical acceleration / discomfort experienced by the driver over 75mm humps and cushions and minimising any differences between driver and passenger. For the bus, minibus and ambulance, the aim is to make discomfort of drivers and passengers no worse than that of car drivers at the same speed.

The criteria for assessing whether changes to hump profiles are an improvement on existing profiles were therefore as follows.

- Average absolute maximum and minimum vertical acceleration not above about 0.7g when speed not above 20mph for the car (15mph for the other vehicles).
- Average absolute maximum and minimum vertical acceleration to increase with speed for the car driver.
- Difference between average absolute maximum and minimum vertical acceleration for driver and passenger to be as small as possible.

From Section 3, peak vertical accelerations over the round top, sinusoidal and flat top humps were above 0.7g for passengers in the taxi and ambulance and bus, even at 15mph. The bus driver also experienced peak acceleration slightly above 0.7g over the flat top and sinusoidal humps at this speed.

For the testing, accelerations were obtained at the driver’s seat and the centre of gravity for the car, taxi, ambulance and bus, and at the rearmost passenger seat for the latter three vehicles, whereas comparisons earlier in

Section 4 were all made at the centre of gravity. Because the simulated values were chassis accelerations, they take no account of the type of seating. This difference will be greatest for the bus driver. However, the relative effect of any change in hump profile should be indicative of the true change in vertical acceleration for the driver and hence of driver comfort.

It must be recognised that the conclusions in this section are based solely on the HVE model and that they apply only to the vehicles tested and to one position of the passenger (the rearmost seat). Different vehicles will vary in the timing of front and rear wheel travel over the humps with respect to suspension compression or extension. In addition, vehicles with slightly differing wheelbases may experience a characteristically different pattern of accelerations when travelling over the same hump. Such effects are considered to be particularly likely where the length of the hump is very close to the wheelbase of the vehicle. Buses with different wheelbases may in any case have significantly different mechanical (particularly suspension) and inertial properties.

No testing was undertaken of humps of different heights since 75mm was shown in earlier studies to be a good compromise between effectiveness and possible grounding (see DfT, 1996b).

#### Round top hump

The effect of crossing a round top hump of length 5m, height 75mm was compared with that of crossing the 3.7m hump used in the physical tests, for the car at the centre of gravity and at the driver’s seat. Generally, the vertical acceleration was slightly lower with the 5m hump, suggesting its speed reducing effect would be less, in line with the findings by Sayer *et al.* (1999).

#### Sinusoidal hump

Humps with a sinusoidal profile are similar to round top humps but have a shallower initial rise. They were developed in the Netherlands and Denmark to provide a more comfortable ride for cyclists in traffic calmed areas. The Dutch sinusoidal hump differs slightly from the UK version (see Figure 28), being 80mm in height rather than 75mm. Its effect on the car was found to be little different to the UK sinusoidal hump.

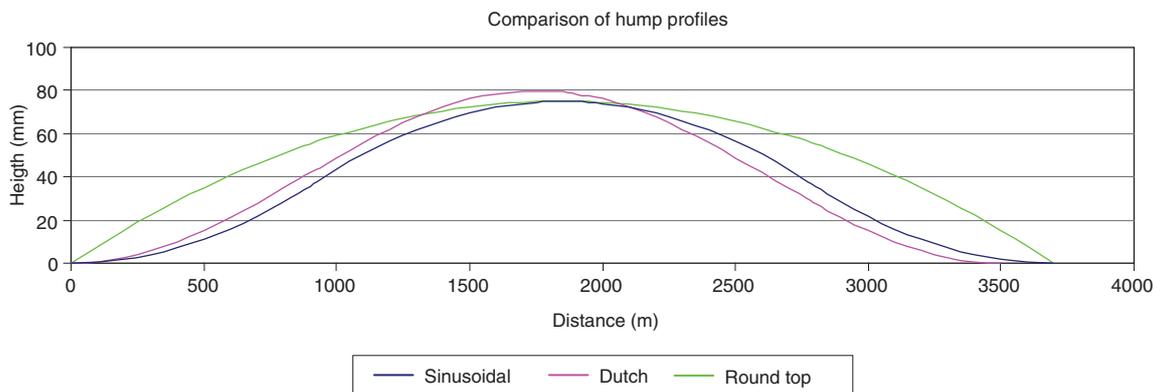
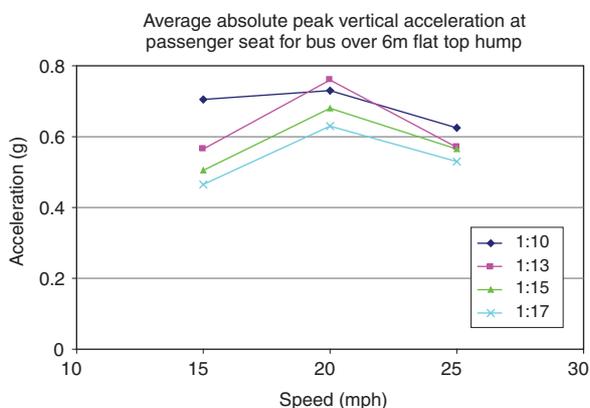


Figure 28 Comparison of round top, UK sinusoidal and Dutch sinusoidal hump profiles (vertical scale exaggerated)

### Flat top hump

The flat top hump used in the physical testing had a 6m long plateau with an on/off ramp gradient of 1:15. Alternative on/off ramp gradients of 1:10, 1:13, (1:15) and 1:17 were tested for the car, taxi, ambulance and bus. In terms of the above criteria, for the car, the acceleration at the driver's seat was too severe with a 1:10 ramp gradient and the 1:17 ramp gradient had the effect that lower accelerations were predicted at higher speeds. For the bus at 15mph, 1:10 was more severe than the other gradients; 1:17 was slightly better for both passenger (Figure 29) and driver, but accelerations were still too high. In the taxi and the ambulance, 1:17 minimised the effect on both driver and passenger, but the differences were not very great and accelerations were still too high for the passenger. Overall, ramp gradients different from 1:15 were not predicted to give any improvement in performance.

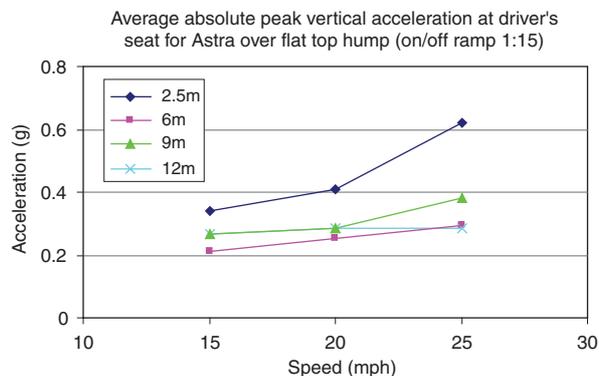


**Figure 29** Average absolute maximum and minimum vertical acceleration at the passenger seat for the bus over flat top humps with different on/off ramp gradients

For a flat top hump with a ramp gradient of 1:15, alternative plateau lengths of 2.5m, (6m), 9m and 12m were tested. At the car driver's seat, a length of 2.5m was more severe than longer humps (Figure 30) and would therefore be likely to have a greater speed-reducing effect. For the bus, 6m was the best for the driver, and 6m or longer for the passenger. For the ambulance, 6m or 9m were best for the driver, and 9m for the passenger. It was concluded that although a plateau length of 2.5m could give improved performance for the car, 6m or 9m would be more appropriate for other vehicles. These results are likely to be affected by the length of the wheelbase of the vehicle tested.

### Speed cushions

The speed cushion used in the physical testing had a height of 75mm, a width of 1.7m, a plateau width of 1.1m, side ramp gradients of 1 in 4, a length of 3.0m, a plateau length of 1.8m and an on/off ramp gradient of 1 in 8. When the cushion is straddled, its dimensions have no effect on bus or ambulance drivers, although their passengers may be affected. With two-wheels on, improvements to discomfort

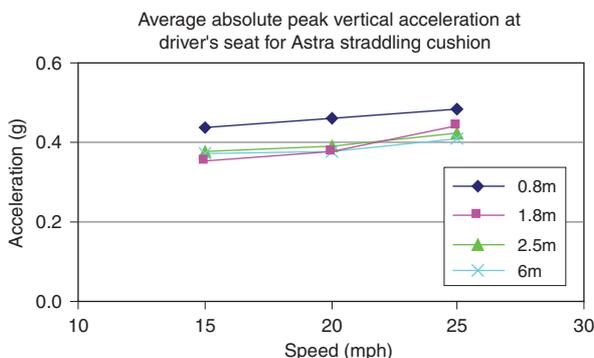


**Figure 30** Average absolute maximum and minimum vertical acceleration at the driver's seat for the car over flat top humps with different plateau lengths

can only be made by altering the gradient of the on/off ramp or the plateau length; changing the plateau width has no effect.

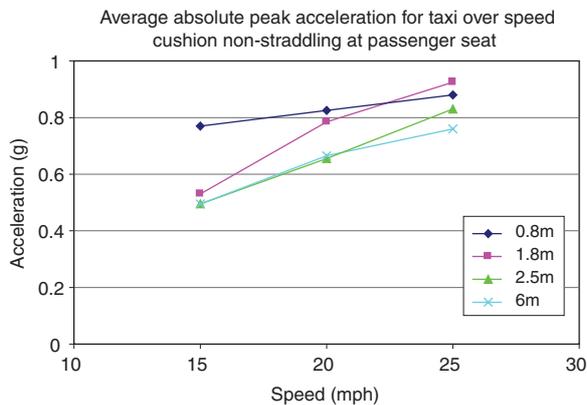
### Speed cushions – plateau length

With the other dimensions kept fixed, various alternative plateau lengths were tested - 0.8m, (1.8m), 2.5m and 6m. When the cushion was straddled, there was little variation with plateau length for any of the vehicles, although for the car at the driver's seat, a length of 0.8m was the most severe (Figure 31), with 1.8m giving a better increase with speed. A length of 2.5m was better for the taxi driver and passenger. There was little effect on bus or ambulance passengers.



**Figure 31** Average absolute maximum and minimum vertical acceleration at driver's seat for car straddling speed cushions with different plateau lengths

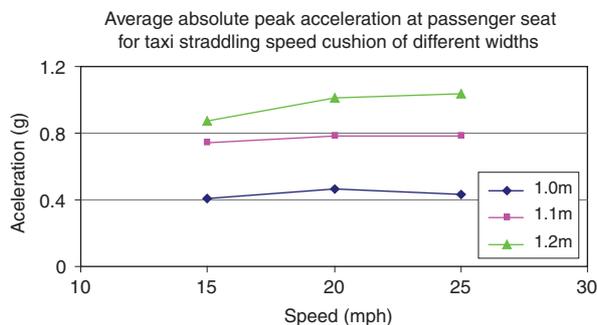
When the cushion was traversed with 2 wheels on, 1.8m was the most effective at the car driver's seat and was also the best at the bus driver's seat, although there was little difference for other lengths. Either 1.8m or 2.5m were best for the taxi driver and 2.5m or 6m for the taxi passenger (Figure 32). For the ambulance, 6m was best for both driver and passenger. It was concluded that plateau lengths different from 1.8m would not improve performance.



**Figure 32** Average absolute maximum and minimum vertical acceleration at rear passenger seat for taxi with 2 wheels on speed cushions with different plateau lengths

#### Speed cushions – plateau width

Similarly, for a plateau length of 1.8m, various alternative plateau widths were tested – 1.0m, (1.1m) and 1.2m – for vehicles straddling the cushion. As expected, a narrower 1m speed cushion was less severe and a wider 1.2m cushion more severe than a 1.1m cushion (see Figure 33 for the rear passenger seat in the taxi), with a width of 1.1m a good compromise.

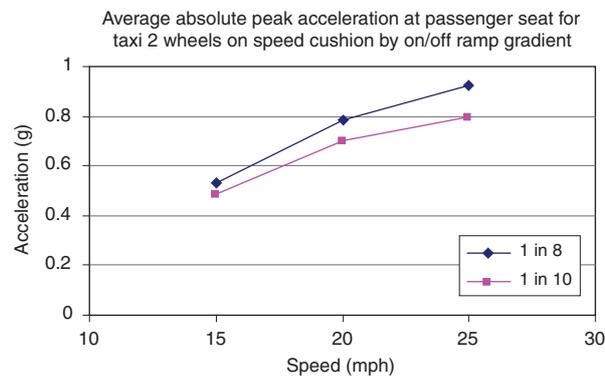


**Figure 33** Average absolute maximum and minimum vertical acceleration at rear passenger seat for taxi straddling speed cushions with different plateau widths

#### Speed cushions – ramp gradients

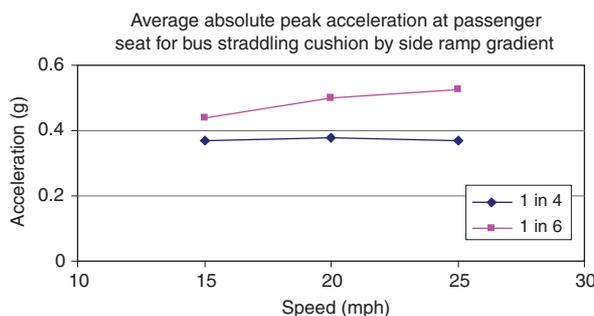
Further tests were undertaken for the car, bus and taxi over a cushion with an alternative 1 in 10 on/off ramp gradient (each keeping other dimensions constant). The 1 in 10 gradient was less severe for the car driver than the 1 in 8 gradient but was little different for the bus driver or passenger. It was slightly better at the passenger seat of the taxi with two wheels on (Figure 34). It was concluded that the 1 in 10 gradient would not give any improvement in the performance of the cushion.

Finally tests were undertaken for the car, bus and taxi straddling a cushion with a 1 in 6 side ramp gradient. This was little different to the 1 in 4 gradient for the car and for



**Figure 34** Average absolute maximum and minimum vertical acceleration at rear passenger seat for taxi over speed cushions (2 wheels on) with different on/off ramp gradients

taxi and bus drivers, but was worse for taxi and bus passengers (see Figure 35 for the bus). It was concluded that a 1 in 6 side ramp gradient would not improve performance of the cushion.



**Figure 35** Average absolute maximum and minimum vertical acceleration at passenger seat for bus straddling cushion with different side ramp gradient lengths

### 4.7 Summary of profile testing

There was no evidence that alternative hump dimensions to those currently recommended could remove any unnecessary discomfort *and* maintain safety objectives. The following hump dimensions mostly gave good speed reductions without excessive discomfort for the occupants of the vehicles tested:

- A height of 75mm.
- A round top hump length of 3.7m.
- A sinusoidal hump length of 3.7m with UK profile.
- A flat top hump plateau length of 6m or 9m and on/off ramp gradient of 1:15.
- A speed cushion length of 3.0m, with 1.8m plateau length, 1:4 side ramp gradient, 1.7m width, 1.1m plateau width and 1:8 on/off ramp gradient.

Speed cushions result in lower peak vertical accelerations than either round top or flat top humps and

are therefore likely to be less effective in reducing the speed of cars, but can be straddled by larger vehicles. They are therefore appropriate on bus routes and strategic routes for emergency services.

Alternative dimensions to those above may be more appropriate in specific situations, for example, where vehicles other than cars predominate.

## 5 Biomechanical modelling

### 5.1 Background

Biomechanical modelling was used to determine the effect on the occupant of a vehicle traversing a road hump. In previous work carried out for the Department for Transport under the New Horizons Programme, a finite element (FE) model of the human spine was created (Sampson *et al.*, 2000). The model comprised detailed geometric representations of the lumbar and thoracic vertebrae and idealised representations of the intervertebral discs and main ligament groups that provide stability to the spinal column. The model was developed with the input of Brian Freeman, Consultant Spinal Surgeon at Queen's Medical Centre, University of Nottingham and was validated against published data on the behaviour of cadaveric spines.

The spine model immediately found two applications:

- Research into whiplash for DfT
- Study of side impact loads to the pelvis, as part of an international programme to develop a new world-harmonised side impact dummy.

Each of these applications required the spine to be loaded in a realistic impact situation. However, the loading on the spine is imposed via the pelvis, thorax, head, neck, etc., and hence a representation of the whole body could be required to place the spine under a representative loading. As a result, two different variations of the spine model evolved as described below.

#### *Whiplash variant*

Whiplash is a forward/rear directional loading, and hence for this application the spine model was integrated with that of a Hybrid III frontal impact dummy. The spine and thorax of the dummy model were replaced with the human spine model and an approximation of the rib cage. A neck model supplied by Nottingham Trent University replaced the dummy neck and the model was validated against volunteer test data.

#### *Side impact variant*

In this case the loading was from the side, and the interaction of the loading mechanism with the pelvis and upper legs was the focus of the work. Of particular interest was the identification of load paths into the spine. Therefore, for this work a representation of the pelvis was developed and validated independently before integration with the spine model. Pre-existing models of human legs were also added to the model, along with the neck model discussed above. The remainder of the body was again

represented by integrating components of a dummy (head, neck, thorax and 'flesh'). The model was validated against cadaveric side impact test data.

The latter model was selected as being the most appropriate for the current work, as it included the pelvis and a representation of the surrounding flesh, both features being necessary for the correct transmission of seat loading into the spine.

Figure 36 shows the FE model of the human dummy in a seated position and Figure 37 shows details of the base of spine and pelvic region.

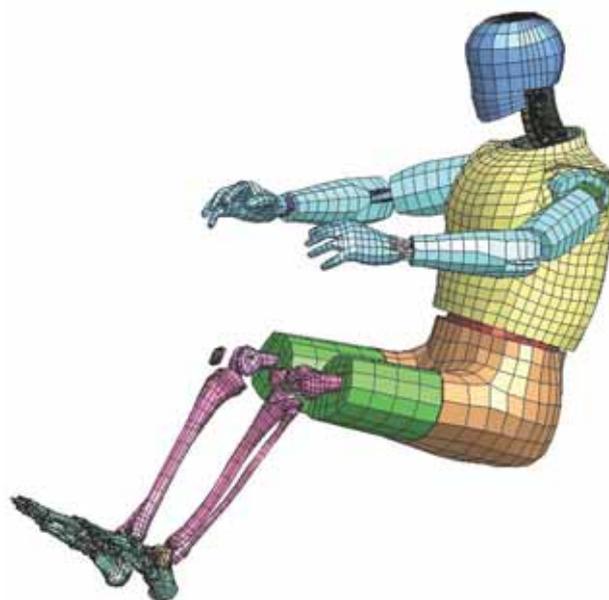


Figure 36 FE model of human dummy

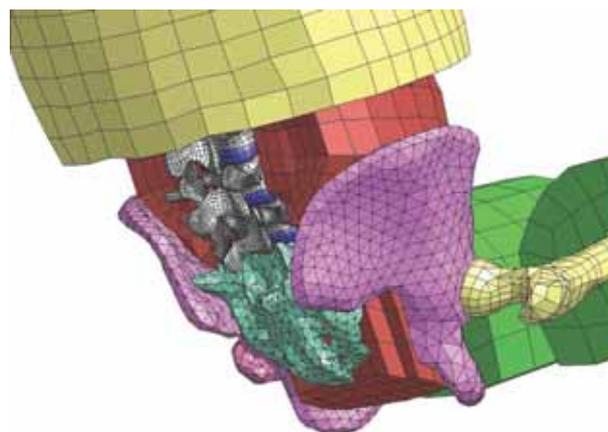


Figure 37 Detail of base of spine and pelvic region

Mr Freeman confirmed that the general approach to the modelling of the human spine was robust and that, of the four main components of the spinal complex – ligaments, muscles, intervertebral discs and the vertebrae themselves – the parameters being recorded from the model (i.e. ligament forces) were appropriate for assessing injury and causation of pain.

## 5.2 Modelling

### 5.2.1 Preliminary work

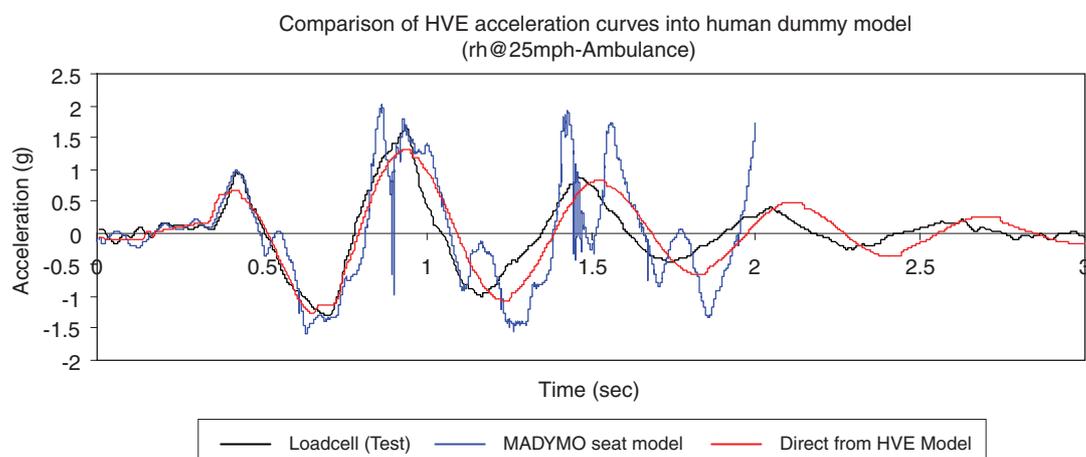
The FE model of the human dummy selected to determine the effect on the occupant of a vehicle traversing a road hump uses the proprietary software code LS-DYNA. However, before the model could be used, a considerable amount of work was carried out to model the seat, update the human dummy and position it in the seat. This process is briefly described below.

The seat was modelled with a stiff back and base plates, where the two plates were inclined to horizontal and vertical planes, such that they were representative of the test vehicle seat. A horizontal foot-plate was also constructed to position the human dummy's feet. The three plates were then connected together such that they moved relative to the vehicle floor. The human dummy was checked for initial penetrations to ensure that a specified minimum gap existed between the surfaces of the different interacting body parts, which would come into contact with each other when the model is run or loaded. This was done in the pelvic region (pelvis, abdomen, lower back and both thighs) and shoulder region (shoulders, upper arms, chest and around the neck) of the model. The human dummy was found to be lighter than the required mass of 75kg and hence additional mass was distributed in the lower parts of the dummy i.e. the abdomen, pelvis, thighs and legs. It was then positioned in the newly constructed seat. The area where the human dummy rested its buttocks and back was modified to provide a smooth interaction between the contacting surfaces. A seatbelt (together with slip rings, retractor and anchorage points) was then constructed and the updated human dummy belted in the new seat and run under a gravitational loading only. During this run, all other forms of loading were switched off. The dummy was found to relax into the seat as expected and this initial behaviour was subsequently incorporated into all runs. This work ensured that the transmission of acceleration, at the seat cushion, into the spine was correct.

In order to obtain the results presented in this section, a loading representing the vehicle in motion as it traversed the hump was established. The model could be loaded using an acceleration applied under the buttocks of the model supplied either directly from the physical test data as acceleration against time or from the Human Vehicle Environment (HVE) model (see Section 4). The acceleration was applied for suitable combinations of road hump design, vehicle speed, occupant type and occupant position.

In order to translate the chassis acceleration from HVE into a seat acceleration under the dummy's buttocks, it was initially planned that a MADYMO human model would be used, seated in a seat model to represent as accurately as possible the interaction between a person and a seat. However, it later became clear that the seat model created in LS-DYNA was sufficient and provided reasonable results, so the MADYMO model was not used.

Figure 38 shows a plot of vertical acceleration against time for an ambulance travelling at 25mph over the round top hump. The 'Loadcell (Test)' curve is taken directly from the loadcell in the pelvis of the rear passenger dummy in the physical testing (Section 3) and is used as the reference. The HVE model provided an initial acceleration curve, which was passed through the MADYMO seat model (where the effect of the seat stiffness was incorporated); the resulting acceleration curve was then applied to the FE model of the human dummy to give the curve labelled the 'MADYMO seat model'. The 'Direct from HVE Model' acceleration curve was derived by applying data from the HVE model directly to the FE human dummy without using the MADYMO seat model. It is clear that this latter curve provides a better correlation than that using output from the MADYMO seat model. One of the reasons for this discrepancy could be that the seat stiffness values used were linear and that in practice the seat behaviour is non-linear. In other words, seat stiffness was not accurately represented in the MADYMO seat model, leading to over prediction and unrealistic behaviour.



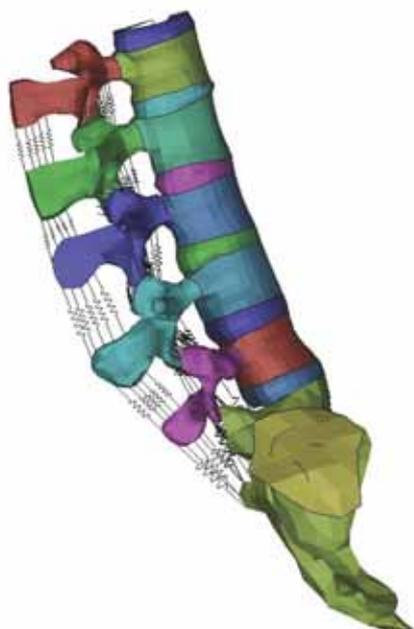
**Figure 38** Comparison of test data acceleration with input data direct from HVE model and using the MADYMO seat model for the ambulance at 25mph over the round top (RH) hump

### 5.2.2 Model outputs relating to discomfort or pain

The outputs from the human dummy model that were considered to relate most closely to discomfort or pain were force and strain (elongation) in the supraspinous ligament (ssl), ligmentum flavum (lf) and capsular ligaments (caps). The report therefore examines the relationships between ligament forces and:

- Shape of acceleration history.
- Speed.
- Vehicle type.
- Hump type.

The values obtained from the model were for the lumbar region only. The lumbar region consists of five vertebrae which are below the thoracic vertebrae and above the fused vertebrae of the sacrum. Figure 39 shows the five vertebrae attached to the sacrum. The upper lumbar vertebra is L1 and the lowest is L5. In between each of these vertebrae is an intervertebral disc (D), where intervertebral disc D1 is between L1 and L2 at the upper end of the lumbar vertebrae and D5 is between L5 and the sacrum at the lower end of the lumbar region.

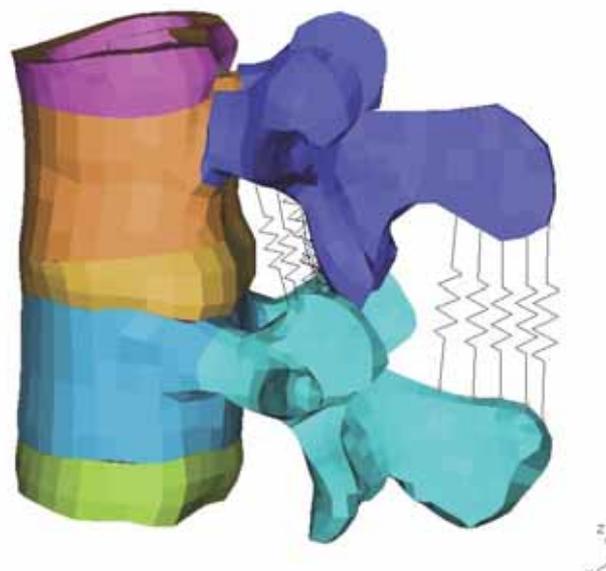


**Figure 39** Lumbar vertebrae, intervertebral discs and ligaments

The three ligaments (described below) are positioned parallel to the spinal cord along the lumbar vertebrae.

The *supraspinous (ssl)* ligament connects along the ‘tips’ of the ‘spinous processes’ and primarily controls bending of the spine, see Figure 40. The spinous processes not only act as sites for the attachment of ligaments but also muscles (not modelled), which control the bending and twisting of the vertebral column.

The *ligmentum flavum (lf)* connects between the inner transverse processes, close to the vertebra facet. Its purpose is similar to the ssl ligament.



**Figure 40** Supraspinous (SSL) and ligmentum flavum (LF) ligaments

The *capsular (caps)* ligament connects the mid-junction between the two transverse processes and helps to keep the vertebral column stable and to provide control of twisting of the spine. The capsular ligament arrangement is shown in Figure 41.



**Figure 41** Capsular (CAPS) ligament

### 5.3 Validation

Data from the physical vehicle testing carried out by Millbrook were used to validate the vehicle occupant model. As explained in Section 2, the test vehicle was fitted with two additional pieces of equipment for this purpose:

- 1 An accelerometer embedded in a rubber seat pad underneath the driver to provide direct acceleration input data for the model.

2 A Hybrid III dummy situated in the rear seat of the vehicle. The position (passenger side or driver side) of this dummy varied depending on which vehicle was being tested.

The Hybrid III dummy was used to output force at the base of the spine itself to validate the transfer of acceleration into the base of the human spine model.

In order to validate the FE model of the human dummy, acceleration data taken from the pad underneath the driver of the test vehicle was applied to the human dummy model and the resulting lumbar loads compared with those measured in the loadcell of the rear passenger dummy in the test vehicle. It should be noted that as the passenger dummy was in the rear of the test vehicle, the comparison was between different positions in the vehicle as well as between the human dummy model and the passenger dummy.

The validation procedure comprised the following steps for each vehicle/hump/speed combination:

- a Extract vertical acceleration data from rubber seat pad under driver.
- b Apply acceleration data to FE human dummy model under its buttocks.
- c Run analysis to the time it takes the vehicle to mount and come off each hump.
- d Extract vertical force (lumbar load) generated from a cross-section through the vertebrae in the lumbar region (the cross-section measures the net force experienced by the spinal column at a given vertebra and does not include the forces generated in the various ligaments attached to it).
- e Extract the vertical force from the load cell in the pelvis of the rear passenger dummy (test data).
- f Compare the force from the load cell (e) with the total cross-section force (d) generated in a given vertebra.

Once validation was complete, the ligament forces and corresponding elongations were extracted for each vehicle/hump/speed combination tested.

Figures 42a-c compare the vertical forces obtained for the car travelling at 15, 25 and 35mph over the round top hump (RH) and show that a speed of 25mph gave the best validation. (Note that due to the distance between the driver and passenger there was a slight time delay in the response measured and that this effect was removed by adjusting the time axis in these figures.) The starting point shown on the x-axis was selected separately for each of the hump/vehicle combinations as the optimum for that set of graphs.

Figures A1 to A4 in Appendix A show the same curves for the car travelling over the flat top (platform) hump (PH), the sinusoidal hump (SH), the speed cushion straddled (CHS) and the speed cushion with 2 wheels on (CH2) respectively. The flat top hump (Figures A1a-c) gave a good result, as did the sinusoidal hump (Figures A2a-c) although the reason for the early peak at 35mph is not clear (Figure A2c). The speed cushion straddled (Figures A3a-c) gave a better validation than with 2 wheels on (Figures A4a-c), which may be due to the off-axis loads generated by the asymmetric vehicle motion. In selecting a best case for further work, those cases generating higher

absolute values of recorded force were considered desirable in order to facilitate comparisons i.e. the sinusoidal and round top humps. Of these two, the round top hump provided a slightly better validation, considering the comments on the early peak described above.

The round top hump and a speed of 25mph were therefore selected for the comparison of results between different vehicles. *The selection of one hump design and one speed helped to reduce the computational effort required to carry out the validation.*

In addition to that using the physical test data, validation was undertaken using vertical acceleration data directly from the HVE model, with the aim of using HVE data for alternative hump designs not included in the physical testing (see Kennedy *et al.*, 2004, for further details). In practice, no alternatives were tested.

Figures 43a-d compare results for the other four vehicles (taxi, ambulance, bus and minibus) travelling over the round top hump at 25mph. The ambulance (Figure 43b) shows a very good comparison up to about 1.4 seconds but after this the simulated force over predicted although it does tend to stabilise after 2 seconds by which time the vehicle has cleared the hump. The minibus in Figure 43d generally provides a good response. Both the taxi (Figure 43a) and the bus (Figure 43c) under predict when compared to the test data. To some extent the response could be explained in the case of the bus as the test dummy was not wearing a seatbelt and this could lead to it moving and hence producing unpredictability in the result. It is more difficult to explain the under prediction for the dummy in the taxi because it was wearing a seatbelt; however, the fact that the applied accelerations were recorded from the driver's position and compared to the dummy forces recorded at the rear seat passenger may be a cause of the discrepancy.

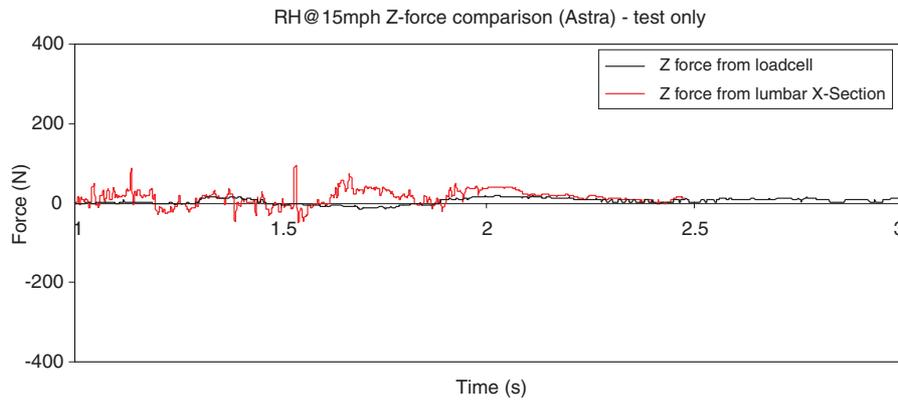
In summary, validation was generally good for the car, ambulance and minibus, but less satisfactory for the taxi and the bus. However, as the same model of the human spine was to be used in all cases, this version was considered appropriate for application in this project.

It will be noted from the graphs that in no case did the force exceed 400N (the maximum being about 370N in Figure 43c for the bus over the round top hump at 25mph).

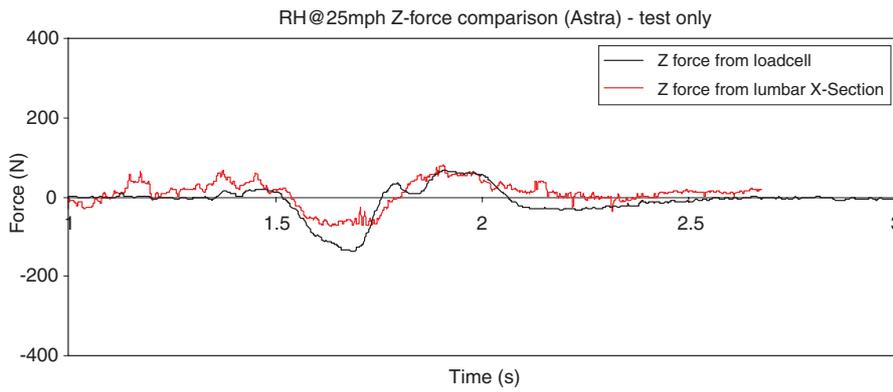
A further validation was performed for the minibus in which the rubber seat pad, previously under the driver, was removed and placed under the Hybrid III dummy in the physical tests. The measured vertical acceleration from the rubber pad was then compared with that obtained from the pelvis of the dummy (see Figure 44). As expected, there was a good correlation between the two, with no time lag since both the pad and the dummy were at the same point.

#### 5.4 Ligament forces

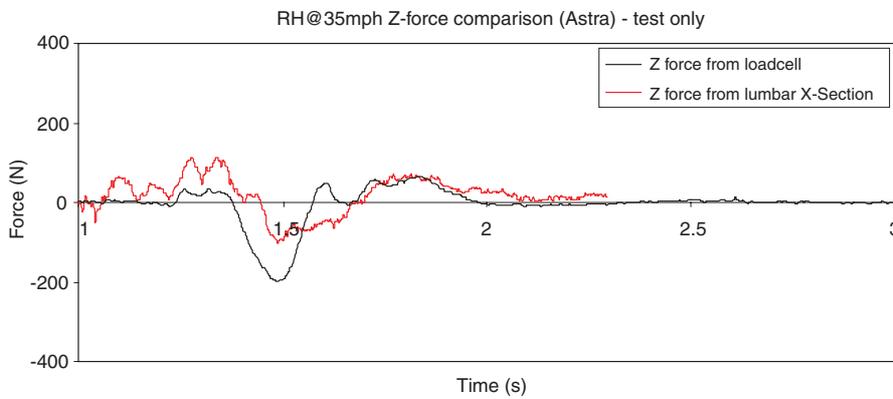
Three ligaments were selected to provide results of axial force and elongation in the lumbar region, as described in Section 5.2.2. A summary of the main results and interpretation is provided below.



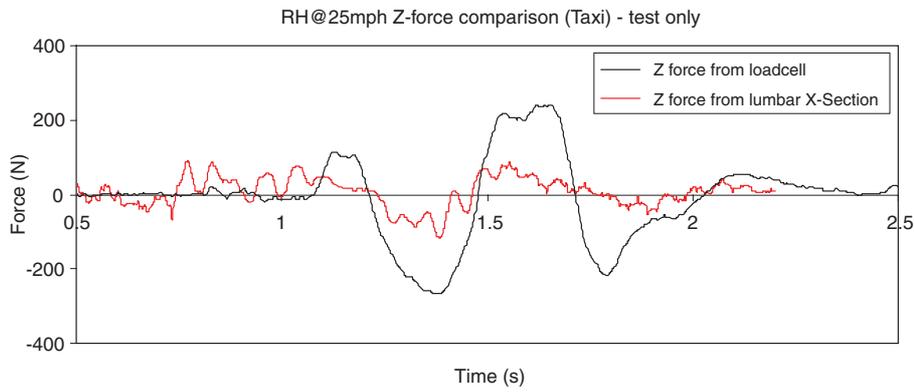
**Figure 42a** Round top hump (RH) at 15mph Z-force comparison for the car – test data



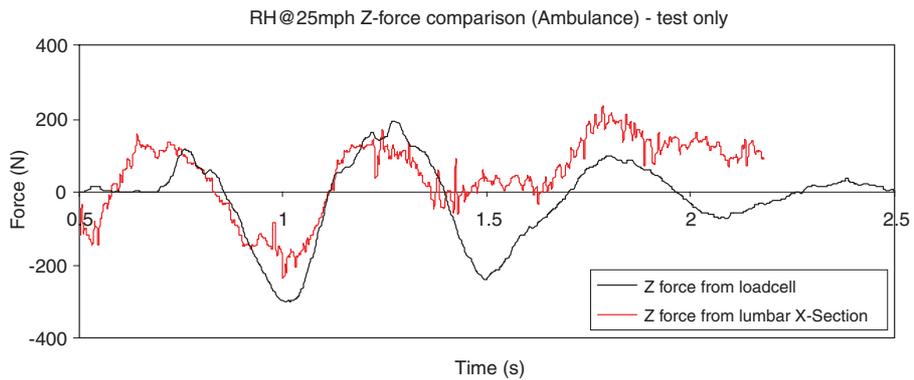
**Figure 42b** Round top hump (RH) at 25mph Z-force comparison for the car – test data



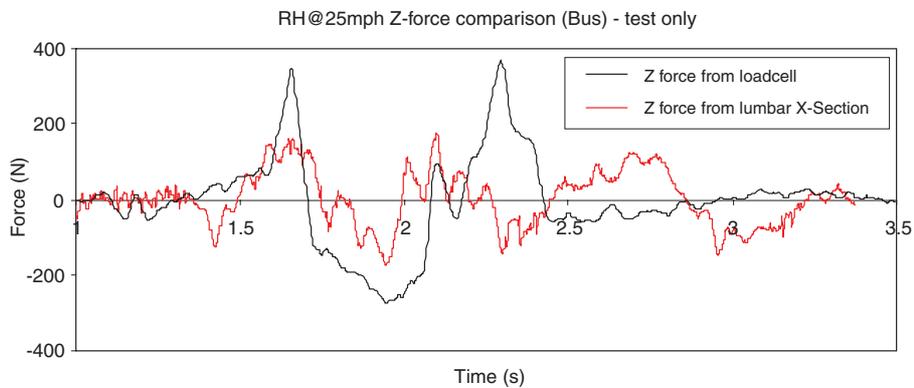
**Figure 42c** Round top hump (RH) at 35mph Z-force comparison for the car – test data



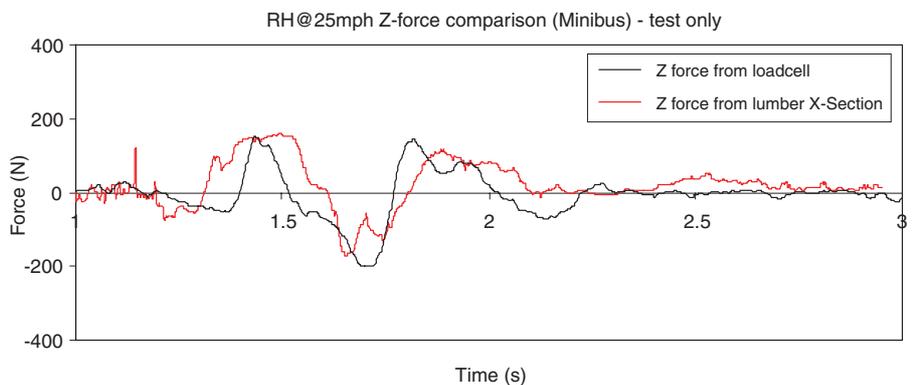
**Figure 43a** Round top hump (RH) at 25mph Z-force comparison for the taxi – test data



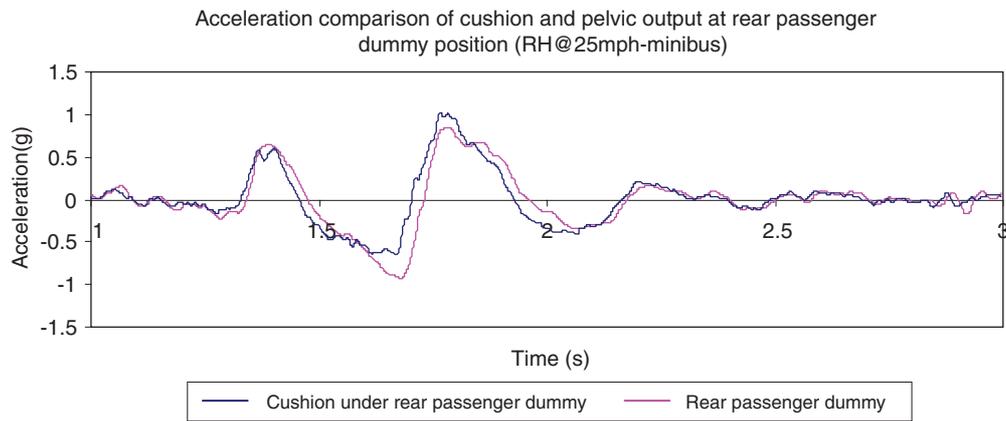
**Figure 43b** Round top hump (RH) at 25mph Z-force comparison for the ambulance – test data



**Figure 43c** Round top hump (RH) at 25mph Z-force comparison for the bus – test data



**Figure 43d** Round top hump (RH) at 25mph Z-force comparison for the minibus – test data



**Figure 44** Comparison of acceleration curves at cushion under rear passenger dummy and in load-cell (Round top hump RH at 25mph, minibus)

#### 5.4.1 Interpretation of results based on physical test data

For each of the five vehicles validated over the round top hump at 25mph, peak ligament forces and elongations were extracted from the FE model for the three ligaments (see Section 5.2.2). These are given in Table B1 in Appendix B, where the negative values of elongation indicate compression; this was ignored for individual ligaments as it implies that the ligament has slackened which is a non-injurious condition.

##### Suprasspinous(ssl)

For the ssl ligament, which largely controls bending of the spine, the highest tensile force of 19.4N (with corresponding extension of 1.1mm) was recorded in the ssl5 ligament when travelling in the ambulance.

##### Ligmentum flavum(lf)

For the lf ligament, which provides similar support to the ssl, the highest tensile force of 11.7N (extension 0.7mm) was recorded in ligament lf5 when travelling in the ambulance.

##### Capsular (caps)

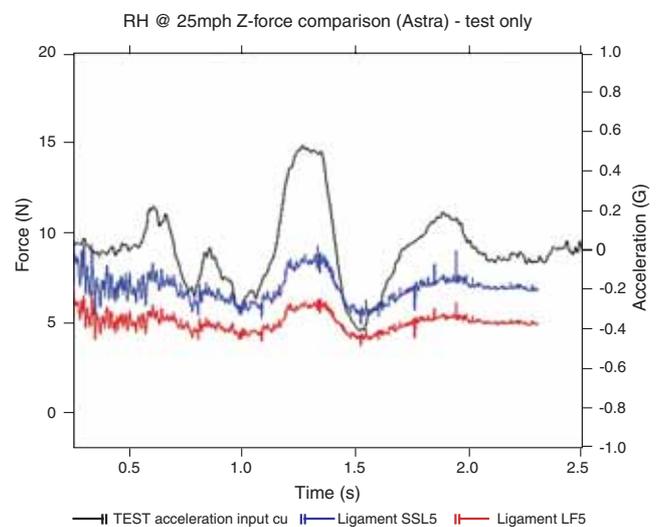
None of the capsular ligaments experienced any tensile force.

#### 5.4.2 Relationship of ligament force to shape of acceleration history

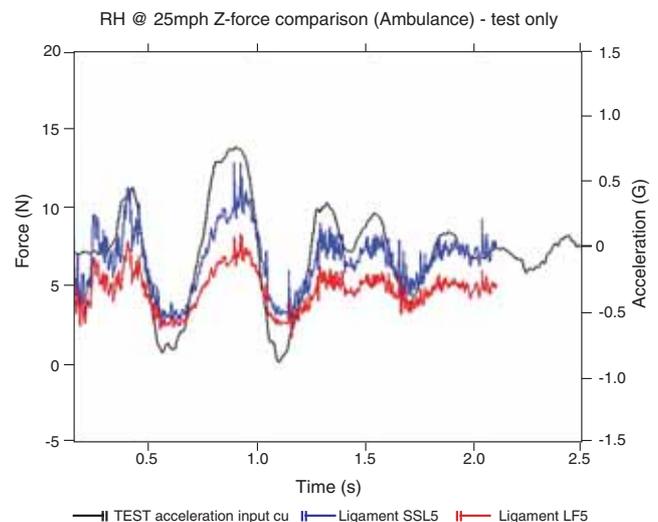
Further plots were generated to demonstrate the relationship between measured parameters and ligament response, as indicated in Section 5.2.2.

Ligament force and vertical acceleration in the vehicle were plotted on the same time axis for the car travelling over the round top hump at 25mph using test data, as shown in Figure 45a. It is clear that any increase or decrease in the gradient in the acceleration curve is matched with a corresponding change in gradient in the forces in the ssl5 and lf5 ligaments and that the forces in the two ligaments increase and decrease in phase with each other.

A similar result was obtained for the ambulance (Figure 45b).



**Figure 45a** Relationship of ligament force to shape of acceleration history in the car at 25mph over the round top hump using test data



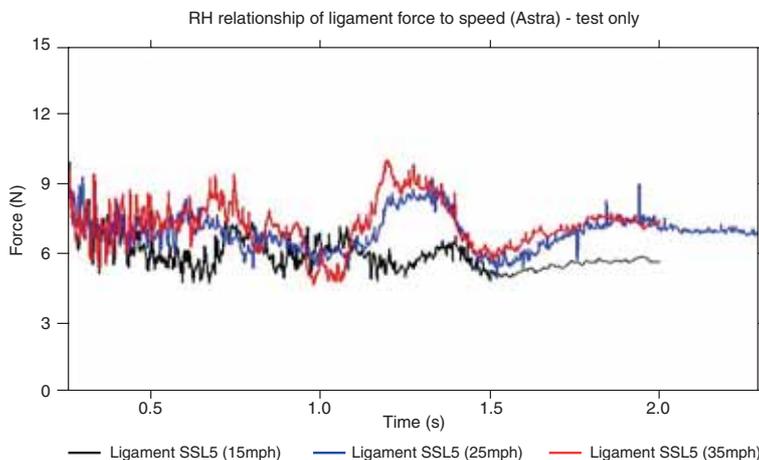
**Figure 45b** Relationship of ligament force to shape of acceleration history in the ambulance at 25mph over the round top hump using test data

The same procedure was undertaken using input acceleration from the HVE model (Kennedy *et al.*, 2004), with similar results. This implies that the acceleration history alone (recorded at the seat) could be used as an indicator of the relative severity of hump profiles in terms of the likely forces on the spine ligaments in future work.

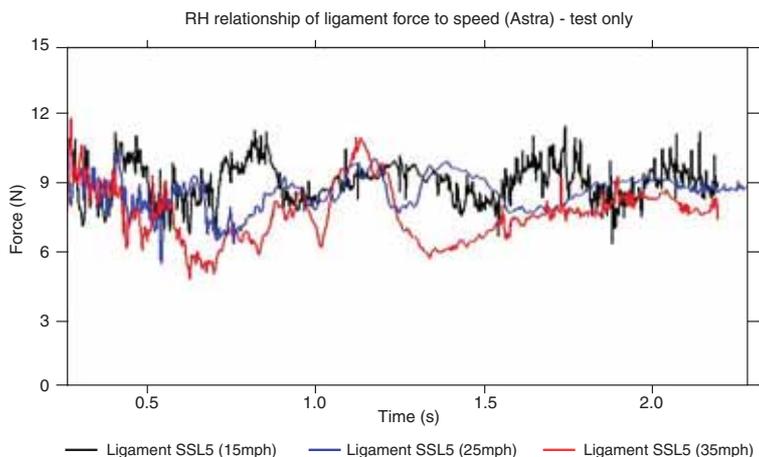
### 5.4.3 Relationship of ligament force to speed

Figures 46a-c show the ssl5 ligament forces using input acceleration from the test data for the car travelling at 15, 25 and 35mph over the round top hump, flat top (platform) and sinusoidal humps.

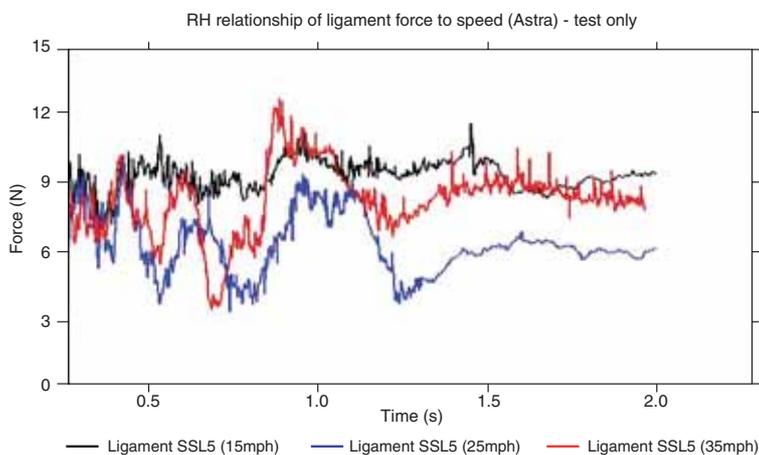
For the round top hump, Figure 46a shows the expected response, that is, as the speed increases so does the overall



**Figure 46a** Relationship of ss15 ligament force to speed for the car over the round top (RH) hump using test data



**Figure 46b** Relationship of ss16 ligament force to speed for the car over the flat top (PH) hump using test data



**Figure 46c** Relationship of ss15 ligament force to speed for the car over the sinusoidal (SH) hump using test data

peak force generated in the ligament.

For the flat top hump, overall maximum and minimum peak values are similar when travelling at 15mph or 25mph, but at 35mph, the trace is out of step (not synchronised) with the lower speeds (Figure 46b).

For the sinusoidal hump, the trace from travelling at 15mph is flatter than those at the higher speeds, which show more variation between the peaks and troughs (see Figure 46c).

#### 5.4.4 Relationship of peak ligament force to hump type

The results for all humps (using test data) were compared for each speed separately when travelling in the car. The values for the forces recorded in the ssl5 ligament are summarised in Table 9, whilst Figure 47 represents graphically the relationship between ligament force and hump type.

**Table 9 Peak ssl5 ligament forces (N) when travelling in the car**

	Round top	Flat top	Sinusoidal	Cushion – straddled	Cushion – 2 wheels on
15mph	12.2	15.1	13.4	13.3	18.2
25mph	13.3	11.7	11.0	13.4	12.3
35mph	15.6	14.0	16.1	8.8	12.5

It is apparent that the type of hump generating the strongest ligament forces depends on vehicle speed. At 15mph, the speed cushion with 2 wheels on (18.2N) was the most severe, followed by the flat top hump (15.1N), with the others all less severe. At 25mph, there was little variation between humps. At 35mph, the sinusoidal (16.1N) and the round top (15.6N) humps were the most severe, with the cushion straddled the least severe (8.8N).

#### 5.4.5 Relationship of ligament force to vehicle type

Where the test data were used as the input vertical acceleration to the FE human dummy model, the vehicle that created the largest peak ligament force over the round top hump at 25mph was the ambulance (ssl5 ligament, 19.4N). The ssl5 ligament also had the peak force for the other vehicles (Table 10).

**Table 10 Peak ligament forces (N) by vehicle type (round top hump at 25mph)<sup>1</sup>**

	Car	Taxi	Ambulance	Bus	Minibus
Test data	13.3	11.2	19.4	13.0	14.5
HVE data	16.8	19.7	11.5	9.7 (ssl2)	15.5

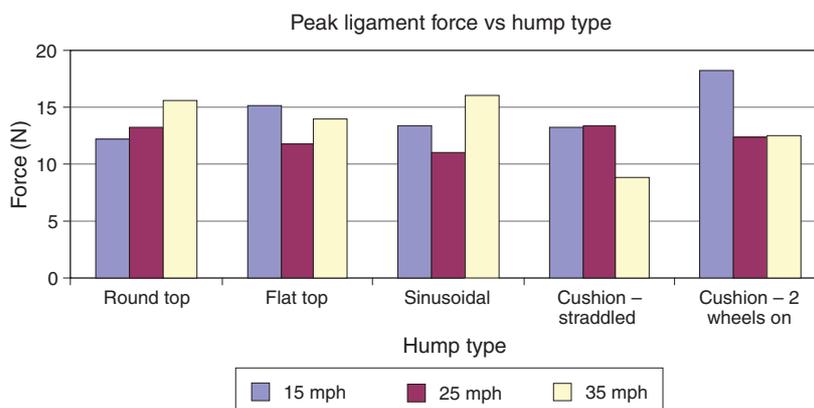
<sup>1</sup> ssl5 ligament except where marked.

A similar result was obtained using input data from the HVE model (see Kennedy *et al.*, 2004, for further details), except that in this case, the largest ligament force (19.7N, again in the ssl5 ligament) was obtained for the taxi. The other vehicles also gave the peak force in the ssl5 ligament, except for the bus for which the ssl2 ligament force was slightly higher (Table 10).

The high forces generated in the ligaments when travelling as a passenger in the ambulance and taxi are in line with the high accelerations for the passenger in these vehicles in the physical testing. Further runs at different speeds over different hump types would be needed to investigate further the effect of vehicle type.

#### 5.5 Summary of finite element modelling

- The FE human model was successfully validated.
- The highest ligament forces obtained were for the ambulance (19.4N) when using acceleration input data from the physical tests and 19.7N for the taxi when using data from the HVE model.
- A relationship has been demonstrated between ligament forces and acceleration history. An increase or decrease in the gradient in the acceleration curve is matched by a corresponding change in the gradient in the ligament forces investigated.
- For the car travelling at 15mph, the hump that gave the greatest ligament force was the speed cushion with 2 wheels on. At 25mph, there was little difference between the effects of different humps. At 35mph, the sinusoidal and the round top humps gave the greatest ligament forces.



**Figure 47** Relationship of peak ligament force (N) to hump type for car occupants

## 5.6 Medical interpretation

Medical interpretation was provided by Brian Freeman who was involved in the original development of the spinal model (see Section 5.1). His comments address the 4 main components of the spinal complex, i.e. ligaments, muscles, intervertebral discs and the vertebrae themselves. In general terms, injuries are frequently seen at the L1 level (the 5th vertebra up from the pelvis), and the most likely part of the spine to be injured as a result of repeated loading would be the intervertebral disc.

### 5.6.1 Ligaments

Ligaments are one of the body parts that do not adapt to their environment, i.e. exercising them will not make them stronger, and also, should they be injured by over-stretching, they will heal in their lengthened state - they do not heal back to their original condition. However, ligaments are fairly elastic and can be extended by about 50% of their length before injury occurs. Therefore, as long as the ligament remains within this elastic range, there is no reason why injury should occur nor why repeated loading should cause an injury.

The model predicted loads up to 20N, whereas the damage threshold of spinal ligaments is in the range of 150-220N (corresponding to 11-26mm of stretch). The forces generated by traversing a road hump are therefore unlikely to be the cause of ligament injury.

Spine ligaments also do not have many nerve endings (with the exception of the capsular ligaments). Therefore, should the spine ligaments be damaged, the pain is not likely to be too noticeable to the patient. It is therefore unlikely that any reported pain is due to ligament damage.

The conclusion is therefore that the spine ligaments are not likely to be injured by traversing a road hump, and repeated loading would not make them any more susceptible to injury.

### 5.6.2 Muscles

Muscle is the most susceptible part of the spine structure to injury. However, although muscle tissue was not modelled explicitly, the fact that the ligaments were loaded so far below their damage threshold can be taken to imply that the muscles would also be very unlikely to be damaged under the loads predicted by the model. Also, muscles tend to add damping to the structure, hence had they been included in the model, the predictions of forces and movements would have been lower, making the model conservative in its predictions.

Unlike ligaments, muscles do adapt to their environment, hence any repeated activity or loading in the muscle will cause it to build up and increase in strength. Hence repeated traversing of a road hump, rather than causing injury, would be more likely to build up the muscle and make it more resistant to injury. In addition, most occupants of a vehicle would be likely to brace in anticipation of traversing a road hump (exceptions being passengers in a bus or in the back of an ambulance). Bracing would also provide resistance to injury.

On this basis, it is again unlikely that muscles would be injured as a result of traversing a road hump, and repeated traversing would, if anything, reduce the likelihood of injury.

### 5.6.3 Discs

The model predicted forces of up to 370N in compression and tension being transmitted through the spine as a whole, i.e. these are the loads that the discs would see. However, the failure load for a healthy disc is about 7000N, and for comparison the forces generated in the disc by heavy lifting are about 1600-2000N. A healthy disc is therefore unlikely to be injured by repeated traversing of a road hump.

However, an unhealthy disc could be at an increased risk of injury. 30% of people over the age of 30 show indications of disc degeneration, and this is made worse if the spine is twisted, or indeed if the patient has recently got out of bed (the discs take on fluid overnight leading to increased tension in the spine - this is gradually squeezed out during the day and the spine relaxes). As a result, excessive exposure to repeated loading for an unhealthy disc could lead to prolapse. However, it should be noted that 'excessive exposure' means more than a few road humps per day, and the amount of loading would have to be more than that expected from even a busy taxi driver in an urban environment. It is therefore considered that injury as a result of traversing road humps would be a very rare event, due to the combined pre-requisite of having an unhealthy disc and the amount of loading necessary.

### 5.6.4 Vertebral fracture

Any vertebral fracture is likely to be due to a pre-existing condition resulting in weak bones, such as osteoporosis, underlying malignancy and myeloma (many of these conditions are particularly associated with the elderly). Hence it is reasonable to say that for those with normal bones, fracture is unlikely, but those with certain pre-existing conditions could be vulnerable.

### 5.6.5 Disability

As there are so many different forms of disability, it is only possible to say that some disabilities could make a vehicle occupant more susceptible to injury as a result of traversing a road hump.

### 5.6.6 Children

Children are generally healthier than adults and their bones more flexible making them generally more resistant to injury, in addition to which the ligaments, muscles and discs of a child are of the same strength as an adult's. The load experienced by a vehicle occupant is related to the mass of that occupant, hence given the lower mass of a child combined with the relatively high tissue strength, a child would be likely to be at lower risk of injury than an adult, assuming that they are properly restrained.

### 5.6.7 Conclusions from medical interpretation

Based on the predictions of the human model used in this work, vehicle occupants are very unlikely to be injured as

a result of single or repeated traversing of road humps. The exceptions to this statement are people with pre-existing conditions that result in either degenerated discs or weak bones, in which case they could be more susceptible to injury depending on the seriousness of their condition.

## 6 Summary and conclusions

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### 6.1 Methodology

The study was based on:

- four different hump types, selected to be representative of those in common use (round top, flat top and sinusoidal humps, and a speed cushion), all 75mm high; and
- five different vehicle types, each representative of models currently found in the vehicle fleet (medium saloon car, London taxi, ambulance, single deck bus and minibus).

Practical vehicle testing at Millbrook Proving Ground was undertaken to determine whether repeatedly traversing road humps causes damage to vehicle components. The tests involved instrumenting the vehicles and recording the response of each vehicle when driven over the humps at different speeds, ranging from 10 to 40mph (10 to 25mph for the bus and the minibus), at 5mph intervals. Vehicle components were examined for possible damage after repeated traversing of the humps. The driver and one or two passengers were asked to rate the discomfort of each hump at each speed for each vehicle.

One of the main outputs from the vehicle testing was the vertical acceleration recorded at different points in the vehicles. The peak vertical acceleration at a particular location in the vehicle (taken as the average of the absolute maximum and minimum values) served as a measure of the discomfort felt by the vehicle occupants. Peak vertical acceleration has been shown to be strongly correlated with discomfort rating: for a given speed, the greater the vertical acceleration, the greater the discomfort. Earlier work has suggested that vehicle occupants are unwilling to accept a peak vertical acceleration of greater than about 0.7g.

The data were also used to validate the computer simulation and the biomechanical modelling at TRL. The computer simulation used a vehicle dynamics simulation model - SIMulation MOdel Non-linear or SIMON - running within Human Vehicle Environment (HVE). It had three purposes:

- to estimate the tri-axial acceleration values at different positions in the vehicle;
- to provide direct inputs to the biomechanical modelling if required; and
- to investigate the effects on vehicle occupants of a wider range of road hump profiles than was possible with the practical testing at Millbrook, with the potential for improving the situations where discomfort is greatest, without increasing the likely speed of traversal of other vehicles.

The biomechanical modelling was used to investigate the physical effect of road humps on vehicle occupants. TRL's existing model of the human spine was developed in order

to estimate the forces in the spinal ligaments of a vehicle occupant when the vehicle traverses a hump, for a range of the hump type / vehicle type / speed combinations.

### 6.2 Effect of humps on the vehicle

The results for the vehicles tested were as follows:

- Visual inspections revealed no damage to any of the vehicles.
- Suspension geometry checks showed small changes in the toe (i.e. the difference between front and rear edges of tyres mounted on an axle) following the passes over the humps and these changes were outside the manufacturers' tolerances for the taxi, the ambulance and the minibus. When the tests were repeated at lower speeds, it was found that the changes remained within the tolerances, provided speeds did not exceed 25mph for the minibus or ambulance and 15mph for the taxi.
- Further investigation of the taxi, in which the forces generated when traversing the hump were simulated, showed that repeated traversals caused the toe to go outside the tolerances temporarily, but that subsequent traversals caused it to return within the tolerances. This suggests that the changes were due to deformation in the compliant elements within the suspension system of this particular vehicle (such as suspension arm bushes, control arm bushes, steering rack mounting, track rod ball joints etc), rather than being an early indication of vehicle damage.
- Four out of the five vehicles showed no change in damping performance following the tests. However, the ambulance showed a reduction in the front suspension damping ratios. As no change was seen in the dampers when tested off the vehicle, this result could be attributed to a reduction in the whole system damping, possibly due to minute changes in the rubber bushes. This represents a normal phenomenon in what was a fairly new vehicle rather than damage or accelerated degradation to the suspension.
- The forces generated by driving over humps at the speeds tested were found to be comparable with those sometimes experienced during normal driving activities, such as driving over a very irregular surface or a pothole, or mounting a kerb.

With the exception of the ambulance, the only changes found in the vehicle components were in the toe angle. The relatively small changes would not be noticeable to the driver in terms of the steering feel or handling, even where the tolerance band was exceeded.

Accelerated tyre wear is a possible effect of toe angle exceeding the tolerance, but it is considered that this would become noticeable to the driver only at greater deviations from specification than those seen during the tests. Since tyres are inspected at the annual MOT test, there is little chance of any defective condition developing that would go unnoticed. Vehicles require periodic adjustment of toe angle during correct maintenance, since driving over normal road features can give gradual toe angle change; that is why tyre centres and garages have the necessary

equipment and have routinely carried out such checks during tyre changes for many decades, not just since road humps have become common.

### 6.3 Discomfort experienced by vehicle occupants when traversing humps

For the vehicles tested in this study, the peak vertical acceleration was below 0.7g for the driver in the car and taxi over the round top, the flat top and the sinusoidal humps at 20mph and in the ambulance and minibus at 15mph, broadly corresponding to subjective ratings in the Millbrook testing of 'slightly uncomfortable' to 'uncomfortable'. Peak acceleration for the bus driver was slightly above 0.7g over the flat top and sinusoidal humps at 15mph. Values for the rear seat passenger were similar to those for the driver in the car at 20mph and the minibus and bus at 15mph.

The peak acceleration for the passenger in the rear of the taxi was much greater (and reported discomfort was also substantially higher) than for the driver, even at 15mph. This may be due to the leaf spring suspension in the taxi tested; the latest models are believed to have coil springs. In the ambulance, the peak acceleration was slightly greater for the passenger in the rear crew seat than for the driver at 15mph, with a much greater differential at higher speeds. Of the full width humps, the flat top hump was better than either the round top or the sinusoidal for the passenger.

The peak vertical acceleration over the cushion was well below 0.7g for both driver and rear seat passenger in most vehicles. For the rear passenger in the taxi and the ambulance, the peak acceleration was higher than for the driver, but still less than for full width humps; straddling the cushion was more comfortable than traversing it with two wheels on. In the trials, the passenger in the ambulance experienced little discomfort when straddling the cushion.

It was concluded that the levels of discomfort associated with measured peak vertical acceleration were generally acceptable if the humps were traversed at appropriate (intended) speeds i.e. not exceeding 15 to 20mph. Although passengers in the rear of taxis suffer considerably more discomfort than drivers, experienced taxi drivers are well aware of this and tend to approach road humps at very low speeds. Ambulance drivers will act in accordance with the situation.

Of the profiles tested, the sinusoidal hump tended to give the highest peak vertical accelerations, but in most cases these were only slightly higher than with the round top hump. Humps with a sinusoidal profile are similar to round top humps but have a shallower initial rise. They were developed in the Netherlands and Denmark to provide a more comfortable ride for cyclists in traffic calmed areas.

### 6.4 Possible alternative hump profiles from HVE computer simulation

From the HVE computer simulation, there was no evidence that alternative hump dimensions to those currently recommended could remove any unnecessary

discomfort *and* maintain safety objectives. The following hump dimensions were considered optimal of those tested, in the sense of maximising discomfort to car drivers at speeds above 20mph:

- A height of 75mm. This was shown in earlier studies to be a good compromise between effectiveness and possible grounding.
- A round top hump length of 3.7m.
- A flat top hump plateau length of 6m to 9m and a ramp gradient of 1:13 to 1:15.
- A speed cushion length of 3.0m, with 1.8m plateau length, 1:4 side ramp gradient, 1.7m width, 1.1m plateau width and 1:8 gradient of on/off ramps.

### 6.5 Biomechanical modelling of effect on spine when traversing humps

In terms of possible damage to the spine, the ligament forces were considered appropriate for assessing injury and causation of pain. From the biomechanical modelling, it was found that:

- Predicted spinal ligament forces were almost an order of magnitude smaller than the damage threshold for such ligaments.
- Predicted forces transmitted through the spine as a whole were at least a factor of 4 smaller than those generated in discs by heavy lifting.

Medical opinion was sought to assist in the interpretation of these results. Because the predicted ligament forces were so far below the damage threshold, it was concluded that ligaments are unlikely to be injured by traversing road humps. Although muscle tissue was not modelled explicitly, this fact can also be taken to imply that the muscles would also be very unlikely to be damaged under the predicted loads.

Similarly, the predicted forces on discs were such that a healthy spine is unlikely to be injured by repeated traversing of a road hump and vertebral fractures are very unlikely to occur for those with normal bones.

Based on these predictions, it is considered that vehicle occupants are very unlikely to be injured as a result of single or repeated traversing of road humps. The exceptions to this statement are people with pre-existing conditions that result in either degenerated discs or weak bones, in which case they could be more susceptible to injury depending on the seriousness of their condition.

### 6.6 Recommendations

- Vertical traffic calming measures (road humps and speed cushions) should continue to be used as an effective method of reducing vehicle speeds, preventing injuries and saving lives. The existing guidance on road hump design should not be altered.
- Where vertical traffic calming measures are required on bus and ambulance routes, speed cushions rather than standard road humps should be used.
- Vehicles should be prevented from parking near to speed cushions to enable buses and ambulances to

straddle the cushions (since discomfort is greater when such vehicles are forced to mount the cushion).

- Taxi design needs to be improved to increase comfort in the rear – this is likely to have a general benefit, particularly for elderly people and those with certain disabilities, but would be especially beneficial in areas with road humps.
- Similarly, ambulance design could be improved to increase comfort in the rear. In particular, the use of vehicles with single rather than double rear wheels would be preferable.
- Road humps need to be carefully built to specification as earlier work has shown that quite small deviations can adversely affect the comfort of vehicle occupants. This is particularly true of the profile at the transition from road to hump.
- Careful attention needs to be paid to the signing and marking of road humps to ensure their visibility, especially at night, and to encourage drivers to slow down in good time for them.

## 7 Acknowledgements

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The authors would like to acknowledge the technical advice from Roger Layfield and Marie Taylor (TRL) throughout the project, and from Brian Freeman, Consultant Spinal Surgeon at Queen's Medical Centre, University of Nottingham, who provided the interpretation of the results for vehicle occupants.

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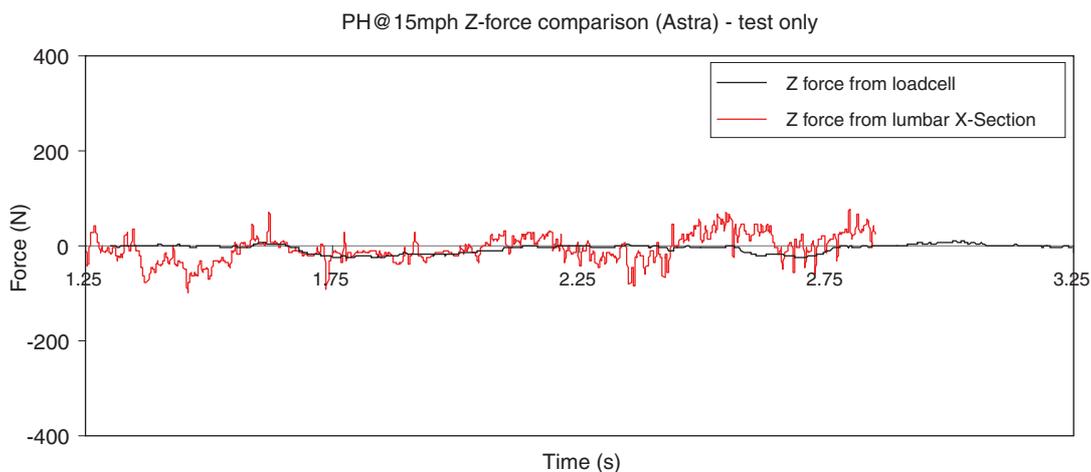
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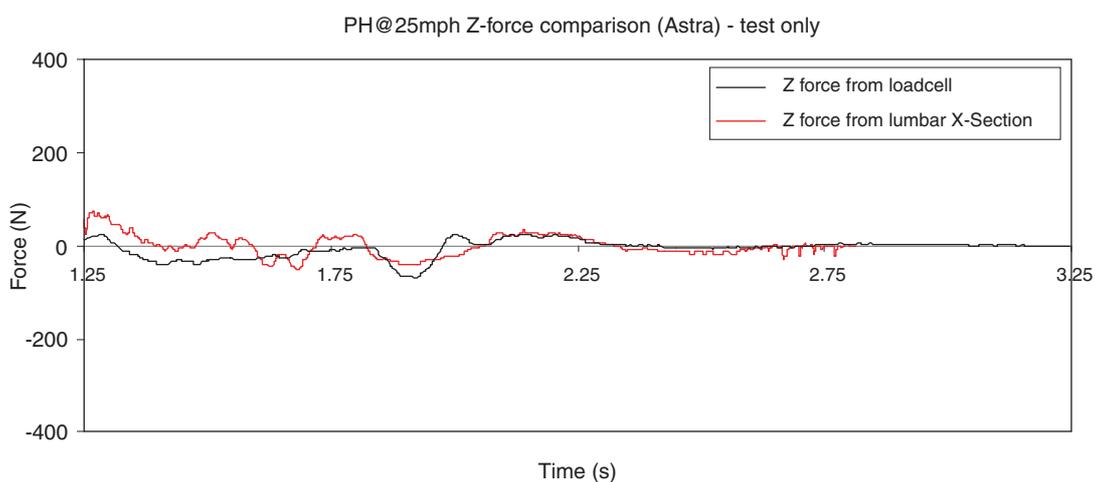
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## Appendix A: Additional results from the biomechanical modelling

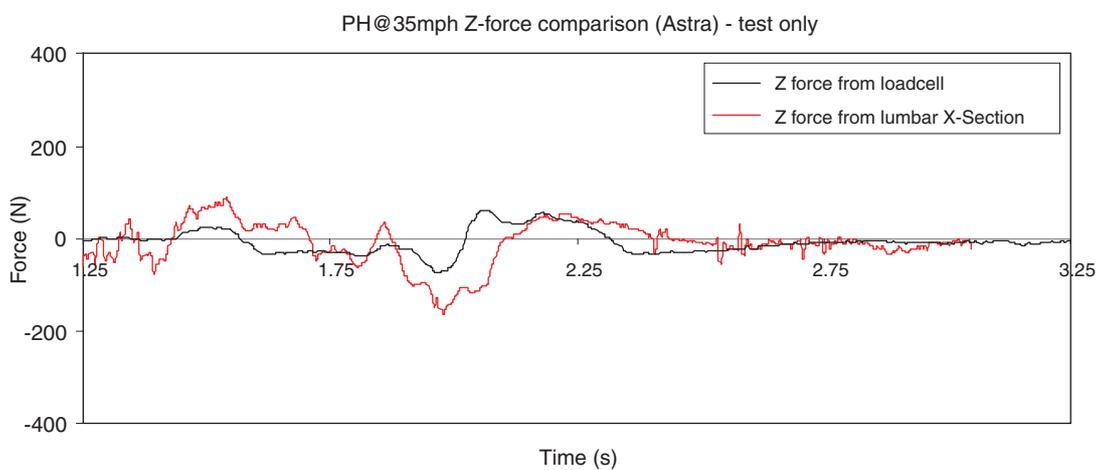
Acceleration based on test data.



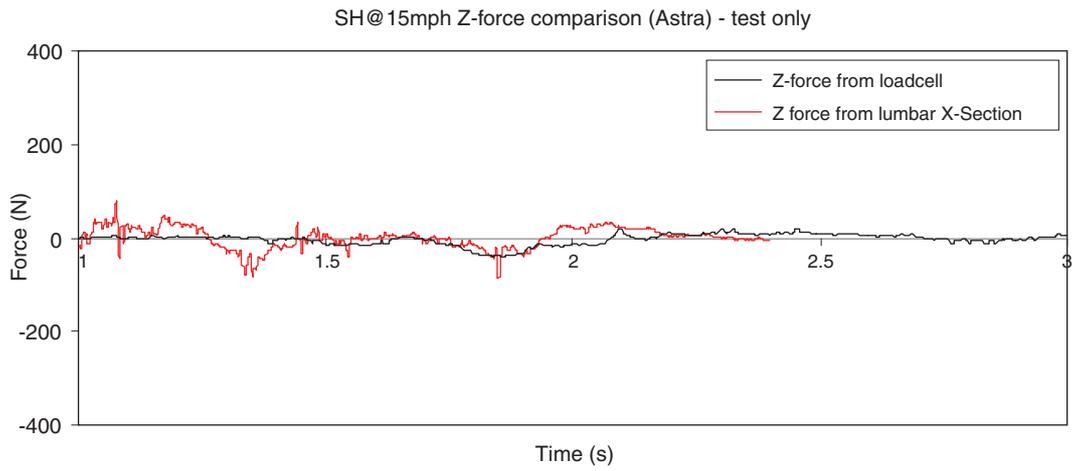
**Figure A1a** Flat top hump (PH) at 15mph Z-force comparison for the car – test only



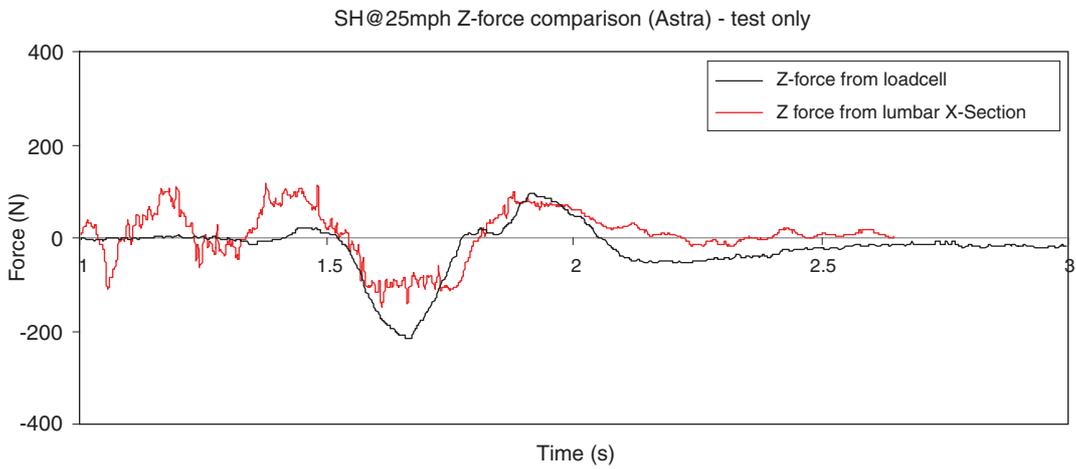
**Figure A1b** Flat top hump (PH) at 25mph Z-force comparison for the car – test only



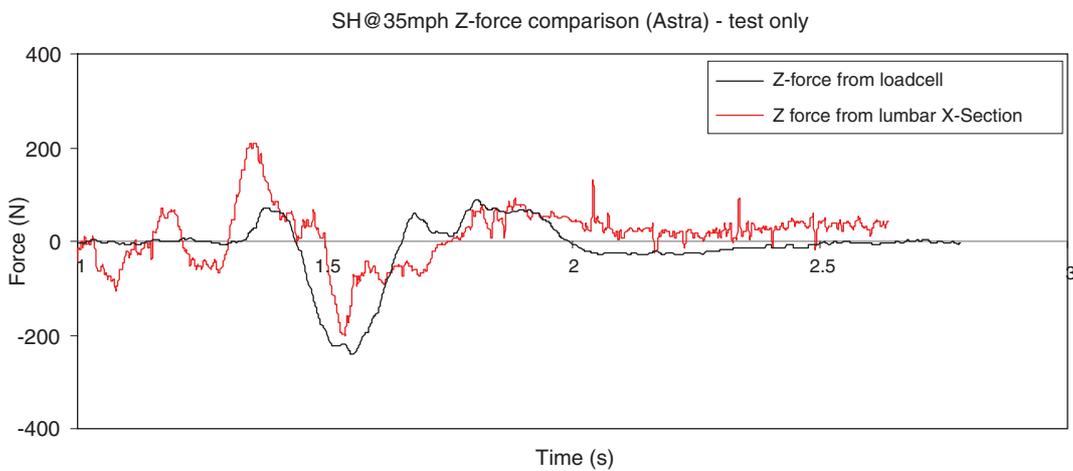
**Figure A1c** Flat top hump (PH) at 35mph Z-force comparison (Astra) – test only



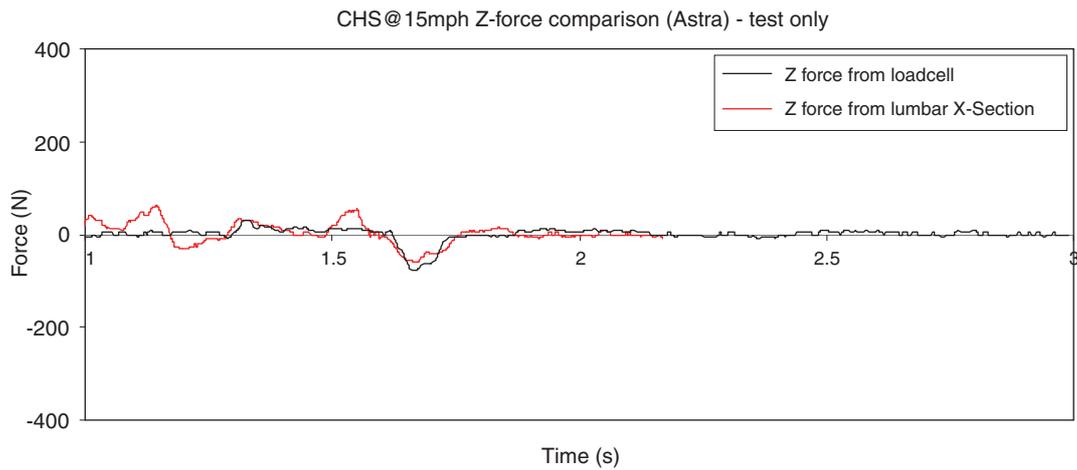
**Figure A2a** Sinusoidal hump (SH) at 15mph Z-force comparison for the car – test only



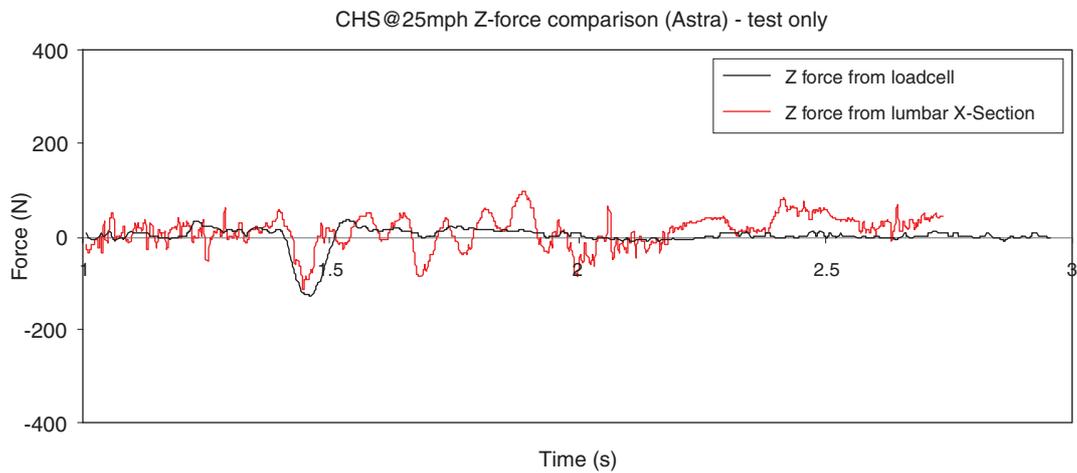
**Figure A2b** Sinusoidal hump (SH) at 25mph Z-force comparison for the car – test only



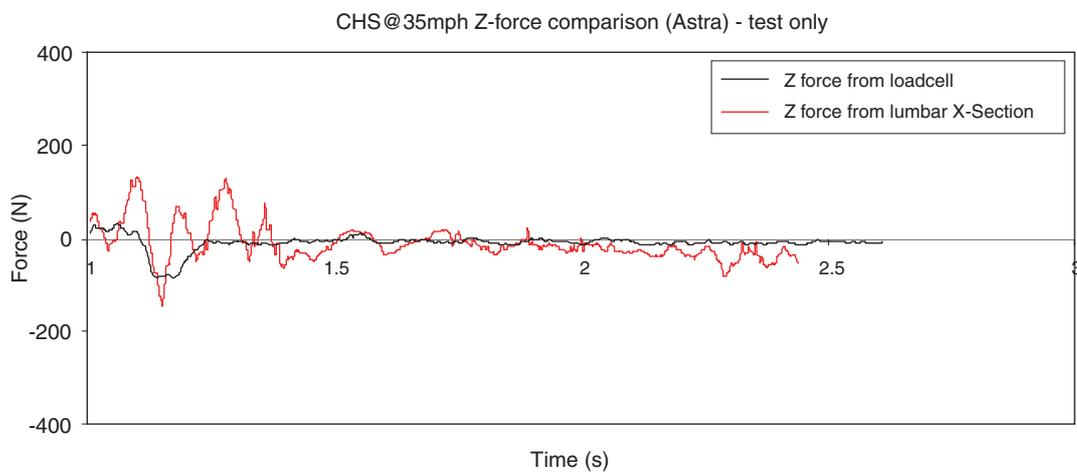
**Figure A2c** Sinusoidal hump (SH) at 35mph Z-force comparison for the car – test only



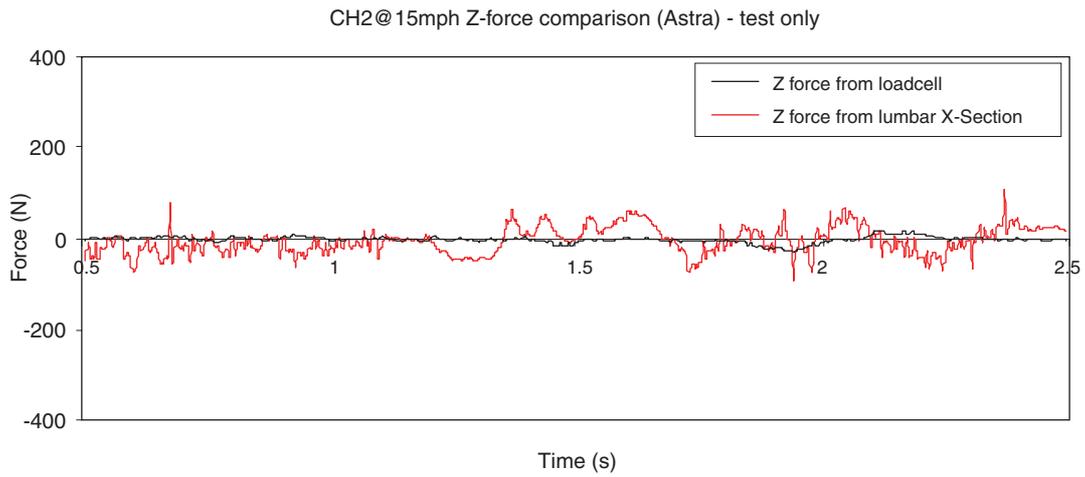
**Figure A3a** Speed cushion straddled (CHS) at 15mph Z-force comparison for the car – test only



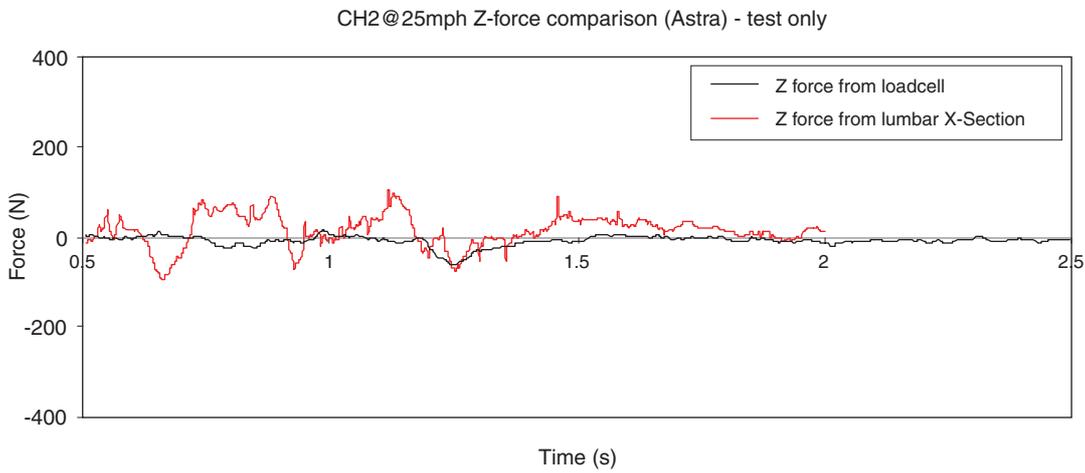
**Figure A3b** Speed cushion straddled (CHS) at 25mph Z-force comparison for the car – test only



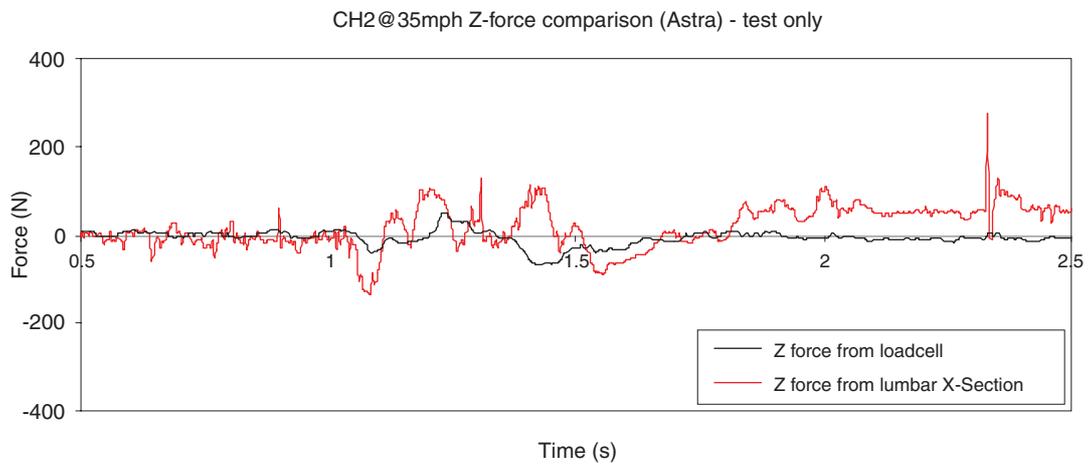
**Figure A3c** Speed cushion straddled (CHS) at 35mph Z-force comparison for the car – test only



**Figure A4a** Speed cushion - two wheels on (CH2) at 15mph Z-force comparison for the car – test only



**Figure A4b** Speed cushion - two wheels on (CH2) at 25mph Z-force comparison for the car – test only



**Figure A4c** Speed cushion- two wheels on (CH2) at 35mph Z-force comparison for the car – test only

## Appendix B: Peak ligament forces from finite element modelling

**Table B1 Peak ligament forces and elongations from FE human dummy model for vehicles travelling over the round top hump at 25mph – test data**

<i>Hump type</i>	<i>Car</i> <i>At 25mph</i>		<i>Taxi</i> <i>At 25mph</i>		<i>Ambulance</i> <i>At 25mph</i>		<i>Minibus</i> <i>At 25mph</i>		<i>Bus</i> <i>At 25mph</i>	
	<i>Force</i> <i>(N)</i>	<i>Elongation</i> <i>(mm)</i>	<i>Force</i> <i>(N)</i>	<i>Elongation</i> <i>(mm)</i>	<i>Force</i> <i>(N)</i>	<i>Elongation</i> <i>(mm)</i>	<i>Force</i> <i>(N)</i>	<i>Elongation</i> <i>(mm)</i>	<i>Force</i> <i>(N)</i>	<i>Elongation</i> <i>(mm)</i>
<b>Round hump</b>										
SSL 1	-0.2	-1.6	-0.2	-1.7	-0.2	-1.8	-0.2	-1.5	5.3	-0.5
SSL 2	-0.3	-3.0	-0.3	-3.0	-0.3	-3.2	-0.3	-3.4	8.8	0.5
SSL 3	-0.1	-1.5	-0.1	-1.2	-0.2	-1.7	-0.2	-2.1	9.1	0.5
SSL 4	4.1	0.2	3.5	0.2	9.5	0.5	3.5	0.2	12.1	0.7
SSL 5	13.3	0.7	11.2	0.6	19.4	1.1	14.5	0.8	13.0	0.7
LF 1	-0.1	-0.7	-0.1	-0.8	-0.1	-0.8	-0.1	-0.7	2.4	-0.2
LF 2	-0.2	-1.5	-0.1	-1.5	-0.2	-1.6	-0.2	-1.6	4.4	-0.6
LF 3	-0.1	-0.8	-0.1	-0.6	-0.1	-0.9	-0.1	-1.0	4.7	0.3
LF 4	3.2	0.2	2.7	0.2	6.3	0.4	2.4	0.1	6.9	0.4
LF 5	9.2	0.5	7.8	0.5	11.7	0.7	9.3	0.5	8.0	0.5
CAPS 1	-0.2	-0.8	-0.2	-0.8	-0.2	-0.8	-0.1	-0.7	0.0	-0.2
CAPS 2	-0.2	-0.7	-0.1	-0.7	-0.1	-0.7	-0.1	-0.6	-0.1	-0.4
CAPS 3	-0.2	-0.9	-0.1	-0.7	-0.2	-1.0	-0.3	-1.3	0.0	0.3
CAPS 4	0.0	0.0	0.0	-0.1	0.0	0.2	0.0	0.0	0.0	0.3
CAPS 5	0.0	0.2	0.0	0.2	0.0	0.3	0.0	0.2	0.0	0.2

Positive and negative values of elongation indicate extension and compression of the ligament respectively.

## Abstract

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A study has been undertaken by TRL and Millbrook Proving Ground for the Charging and Local Transport Division of the Department for Transport (DfT) to examine the impact of road humps on vehicles and their occupants. It involved testing of vehicles driven repeatedly over road humps, computer modelling of the road humps and vehicles, and biomechanical modelling of the human spine.

Road humps have been shown in a number of studies to reduce vehicle speeds and accident frequency. They are the most effective traffic calming device currently available and are likely to be in common use for some time. In general, levels of discomfort are higher when humps are traversed at higher speeds and therefore humps cause discomfort to vehicle occupants if their vehicle is travelling too fast. This increased discomfort is the mechanism which persuades drivers to slow down.

The widespread use of road humps has resulted in some members of the public complaining that humps cause long term damage to vehicle components, especially the suspension, and that they can cause damage to the undersides of vehicles with low ground clearance or to exhausts. Concern has also been raised about whether the use of road humps might cause or exacerbate back or other injuries.

The study aimed to investigate objectively the possibility that road humps cause increased wear to vehicle components and injury to vehicle occupants and to suggest how these problems, if they exist, can be ameliorated.

## Related publications

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TRL417 *Traffic calming: passenger and rider discomfort at sinusoidal, round top and flat top humps - a track trial at TRL* by I A Sayer, D A Nicholls and R E Layfield. 1999 (price £35, code J)

TRL416 *Traffic calming: Vehicle generated noise and ground-borne vibration alongside sinusoidal, round-top and flat-top road humps* by G J Harris, R E Stait, P G Abbott and G R Watts. 1999 (price £35, code J)

TRL215 *Review of traffic calming schemes in 20mph zones* by D C Webster and A M Mackie. 1996 (price £35, code H)

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