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INVESTIGATING THE USE OF SIMULATION MODEL NON-LINEAR (SIMON) FOR THE 'VIRTUAL TESTING' OF ROAD HUMPS

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Abstract

This paper presents the results of a study which involved the measurement of various vehicles responses to being driven over various types of road hump at a range of speeds. The study used measured data such as driver's seat vertical acceleration for biomechanical modelling of the human response to repeated travel over road humps. As part of this project, computer simulation runs were conducted using SIMON to investigate the use of this program for the 'virtual testing' of future road hump designs.

This paper compares the results of physical tests and 'virtual tests' for five different vehicle types travelling over four different designs of road hump, with each vehicle being tested at speeds of up to 40mph. Vehicle types include a passenger car with independent suspension, a taxi and a minibus, both with solid axle suspensions, and a bus and ambulance with airbag suspensions. The methods by which input parameters were measured for each vehicle are described.

Results are presented for COG vertical acceleration, wheel vertical displacement and pitch angle/rate. These show good consistency between physical and test data. It was found that sensitivity tests of key variables allowed a 'best fit' between the simulation and physical test results to be developed. The paper comments on issues arising from the use of measured vehicle parameters, and the sensitivity tests that were undertaken to generate a 'best fit' between virtual and physical tests.

Introduction

As part of a detailed study on the effect of road humps on vehicles and drivers, TRL limited have undertaken an extensive test programme encompassing various vehicle and road hump types. As part of this work the results of the physical tests have been compared to the results of virtual tests using SIMON.

One of the primary aims of TRL's research in this area was to investigate the potential for the use of 'virtual testing' in road hump design, using Human Vehicle Environment (HVE) software and SIMON.

By comparing the results of physical tests with the results of 'virtual' tests, the ability of the SIMON model to predict the vehicle motion observed in the physical tests has been examined.

The vehicle testing elements of this research were conducted at the Millbrook Proving Ground, Bedfordshire, UK. These elements involved the running of the physical tests, including the instrumentation of vehicles and recording of data. Millbrook also undertook measurements of the test vehicles to examine the mechanical effects of repeated exposure to road humps. Additional measurements were taken to provide key input parameters to the SIMON model for each vehicle.

The five vehicles tested during this research were:

- Medium sized hatchback car

  The car tested was a 2001/2002 1.6 litre Vauxhall Astra. This vehicle was selected as a typical medium sized hatchback, Figure 1. At the start of the trials the Astra had 1660 miles showing on the odometer.

- London taxi

  The taxi tested was a 2000/2001 LTI TXi, typical of those used in the London metropolitan area, Figure 2. At the start of the trials the Taxi had 23,745 miles showing on the odometer.

- Ambulance

  The ambulance tested was a Ford Transit emergency response vehicle with rear air suspension, Figure 3. At the start of the trials the Ambulance had 2,316 miles showing on the odometer.

- Single deck bus

  The bus was a 11.8m low floor (Disability Discrimination Act compliant) single deck bus with a Volvo chassis and a Robert Wright body, Figure 4. The vehicle was equipped with a full air suspension system. At the start of the trials the bus had 15,247 miles showing on the odometer.

- Minibus

  The minibus was a 2000/2001, 12 seater Vauxhall Movano, Figure 5. At the start of the trials the minibus had 2,871 miles showing on the odometer.

Each of the above vehicles was tested over four different types of road hump.

Each hump was 75mm high. This height has been adopted by many highway authorities in the UK as it provides a compromise between speed reduction and hump severity. The set of road humps tested comprised:

- Round-top hump, Figure 6 - length 3.7m;
- Flat-top hump, Figure 7 - plateau length 6m with straight, 1:15 gradient, on/off ramps;
- Sinusoidal hump, Figure 8 - length 3.7m;
- Speed cushion, Figure 9 - length 3.0m, width 1.7m, 1:4 gradient side ramps, 1:8 gradient on/off ramps.

Table 1 Summary of test vehicle characteristics

Vehicle	Make	Year of registration	Mileage	Front suspension	Rear suspension
Medium Saloon Car	Vauxhall Astra	2001/2002	1,660	Coil springs	Coil springs
London Taxi	LTI TX1	2000/2001	23,745	Leaf springs	Leaf springs
Ambulance	Modular	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

Figure 1 Vauxhall Astra

Figure 2 London Taxi

Figure 3 Ambulance

Figure 4 Single Deck Bus

Figure 5 Minibus

Figure 6 Round-top hump

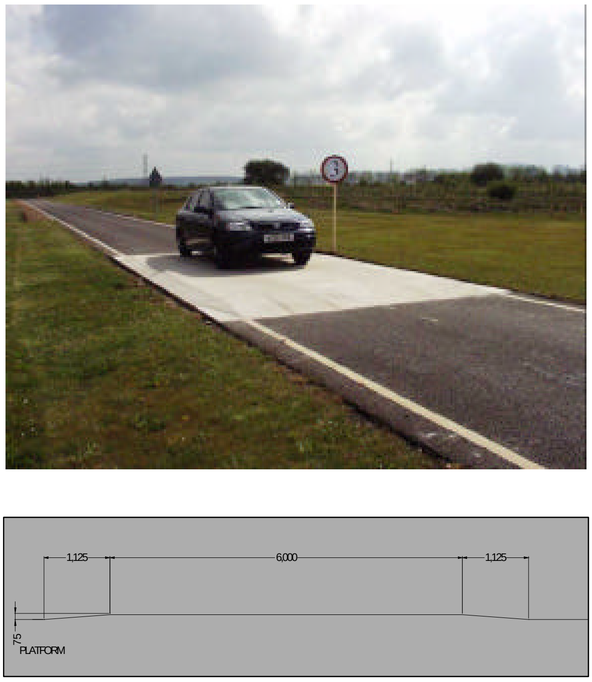

Figure 7 Flat-top hump

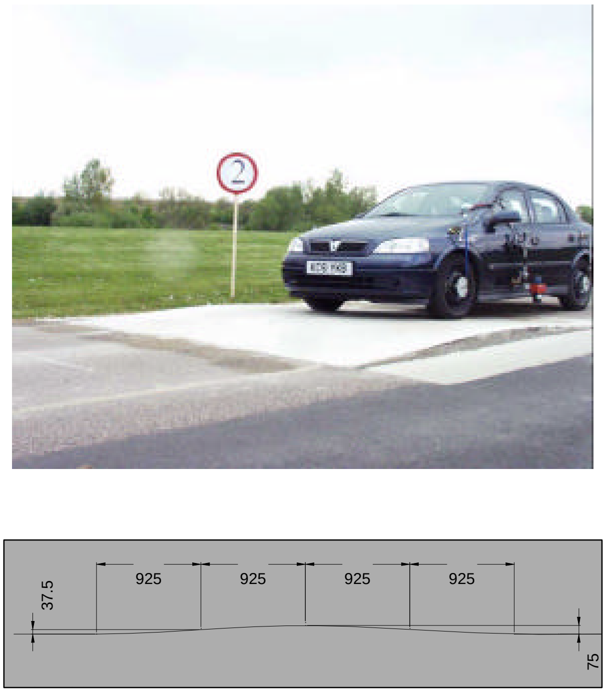

Figure 8 Sinusoidal hump

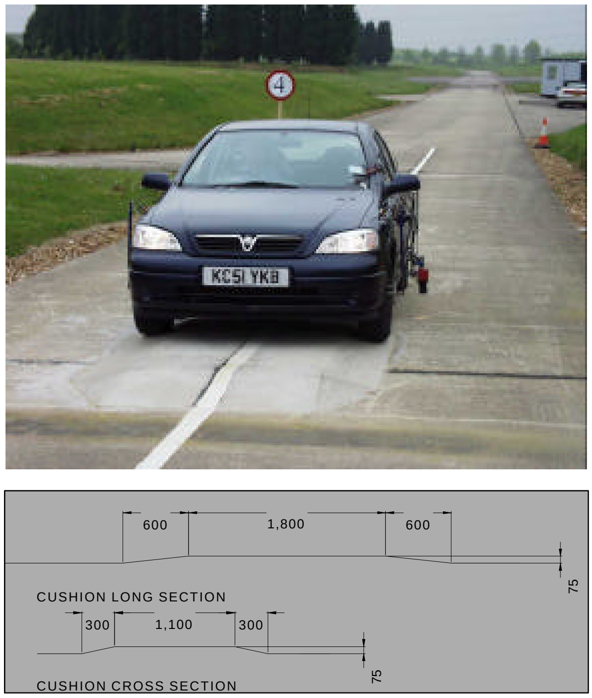

Figure 9 Speed cushion

Methodology

During the testing phase of this research each vehicle was driven over each hump at speeds of between 10 and 40mph, at 5mph intervals. Each vehicle was driven over each hump five times at each speed, with the exception of the bus and minibus at speeds of 30, 35 and 40mph, where only two tests were conducted per speed increment.

Each vehicle was loaded with an instrumented Hybrid III 50%ile (75kg) dummy, positioned in a passenger seat in the rear of the vehicle.

The physical test programme utilised Millbrook's in-house professional test drivers. For all tests the drivers were instructed to approach the humps at speeds as close as possible to the test speed without applying acceleration or braking as the vehicle crossed the hump. In all cases the angle of vehicle travel across the hump was 90 degrees.

<u>Vehicle Measurements</u>

To provide input parameters for the HVE vehicle models to be used in the comparative simulation runs, a number of measurements were made (where possible) for each vehicle.

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

The total mass of each vehicle was recorded using weigh pads under each wheel/set of wheels. The vehicles were weighed both with and without the instrumented dummies.

Centre of gravity measurements were made to identify the height and longitudinal position of each vehicle's centre of gravity (COG). This process was performed using weigh pads under the front and rear wheels in turn, with the opposite end of the vehicle being lifted to a known height. This process was performed with and without the instrumented dummies in the vehicle.

The geometry of each vehicle was also measured in order to provide HVE input variables, these being:

- Overall length (mm);
- Overall width (mm);
- Wheelbase (mm);
- Front track width inner / outer (mm);

Table 2 Typical Sequence of Physical Testing

Test	**Test Speeds**	**Number of Passes**
Round Hump	10 – 40 mph (5 mph increments)	35 Total (5 at each speed)
Platform Hump	10 – 40 mph (5 mph increments)	35 Total (5 at each speed)
Sinusoidal Hump	10 – 40 mph (5 mph increments)	35 Total (5 at each speed)
Cushion Hump (*straddle* – vehicle crossing over centre of hump)	10 – 40 mph (5 mph increments)	35 Total (5 at each speed)
Cushion Hump (*not straddle* – one side of vehicle only crossing hump)	10 – 40 mph (5 mph increments)	35 Total (5 at each speed)

- Rear track width inner / outer (mm);
- Front / rear overhang (measured from wheel centre) (mm);
- Maximum positive / negative suspension deflection (mm) – front/rear;
- Front / rear loaded tyre radius at test weight (mm);
- Mass of wheels (kg).

The front and rear static spring rates of each vehicle were measured before and after the dynamic testing. For each vehicle with coil or leaf springs the vehicle was loaded in increments of approximately 30 kg per wheel. The vehicle was then moved a short distance to allow the suspension to settle, and the ride heights were measured.

The results for ride height verses load were plotted and the spring rates ascertained.

The suspension stiffness of the single deck bus could not be physically measured as its air suspension system on both the front and rear axles continually adjusts 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.

The dampers on each test vehicle were removed from the vehicle and subjected to carding tests before (and after) the physical testing. Dampers from the Vauxhall Astra, the taxi and the minibus were tested at frequencies of 0.1 Hz, 0.5 Hz, 1.0 Hz, 1.5 Hz and 2.0 Hz, all at an amplitude of $\pm$ 40 mm. The dampers from the single deck bus were tested at the same frequencies at an amplitude of $\pm$ 50 mm. The dampers from the ambulance were tested at frequencies of 0.1 Hz, 0.5 Hz, 1.0 Hz and 1.5 Hz, all at an amplitude of $\pm$ 50 mm.

The carding tests were conducted to monitor any deterioration of the dampers from the testing. Comparison of before and after data showed no significant deterioration for all test vehicles.

The carding tests also demonstrated the velocity dependency of the dampers fitted to the test vehicles by examining the performance of each damper at different frequencies.

The limitation of the carding tests is that they only demonstrated the damping properties of each damper in isolation. Therefore, to calculate the rate of damping for each test vehicle a number of drop tests were conducted. These drop tests demonstrate damping properties for the whole suspension system.

For the drop tests one end of the vehicle was raised so that the wheels were off the ground, then dropped freely onto its wheels. The wheels at the opposite end of the vehicle remained static on the ground, with the suspension locked to prevent movement. Displacement transducers, fitted to the four wheels, recorded wheel displacement relative to the vehicle body.

This test was carried out on both the front and rear suspension, prior to and following the dynamic testing.

Time history plots of the logarithmic decrement of damping were generated and used to calculate a damping ratio for each wheel. The calculated damping ratio, together with the measured spring rate and vehicle corner sprung mass, was used to calculate the rate of damping for each vehicle axle. These damping rates were then adopted for the *'Damping at wheel N-sec/m'* shock absorber parameter in the *'Spring and Shocks'* dialogue box of the HVE Vehicle Editor.

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. Tolerances for the total toe measurements were monitored against manufacturer specifications.

As part of the set up of the 'virtual' test vehicles (using the HVE vehicle editor), tyres were selected that were either of the same size/aspect ratio as those fitted to the test vehicle, or that were as close as possible to those fitted to the test vehicle.

Vehicle inertia properties were calculated using the measured vehicle dimensions.

<u>Instrumentation</u>

For the physical tests each vehicle was fitted with a number of sensors linked to a Micro Movements M4000R Data Acquisition Recorder. This was set up to record all channels simultaneously at a sample rate of 500 Hz.

A total of 30 data channels were recorded for each vehicle during the trials. Of particular relevance to the comparison between the physical and 'virtual' HVE tests were the following:

- 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.

Results

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 and 'virtual' tests focused on matching the respective vertical acceleration profiles.

Measurements obtained from the physical tests were observed to show a high level of consistency and repeatability. This is illustrated by the five vertical acceleration profiles recorded for the Astra travelling over the round-top hump at 30 mph, Figure 10.

In assessing the consistency between the results of the physical tests and the simulation tests a number of key parameters have been examined, these being:

- COG vertical acceleration;
- wheel vertical displacement;
- pitch angle and pitch rate.

Exemplar physical and simulation test data are presented graphically in Figures 11 to 16. These figures present a cross section of 'typical' results for each vehicle, test speed and road hump type.

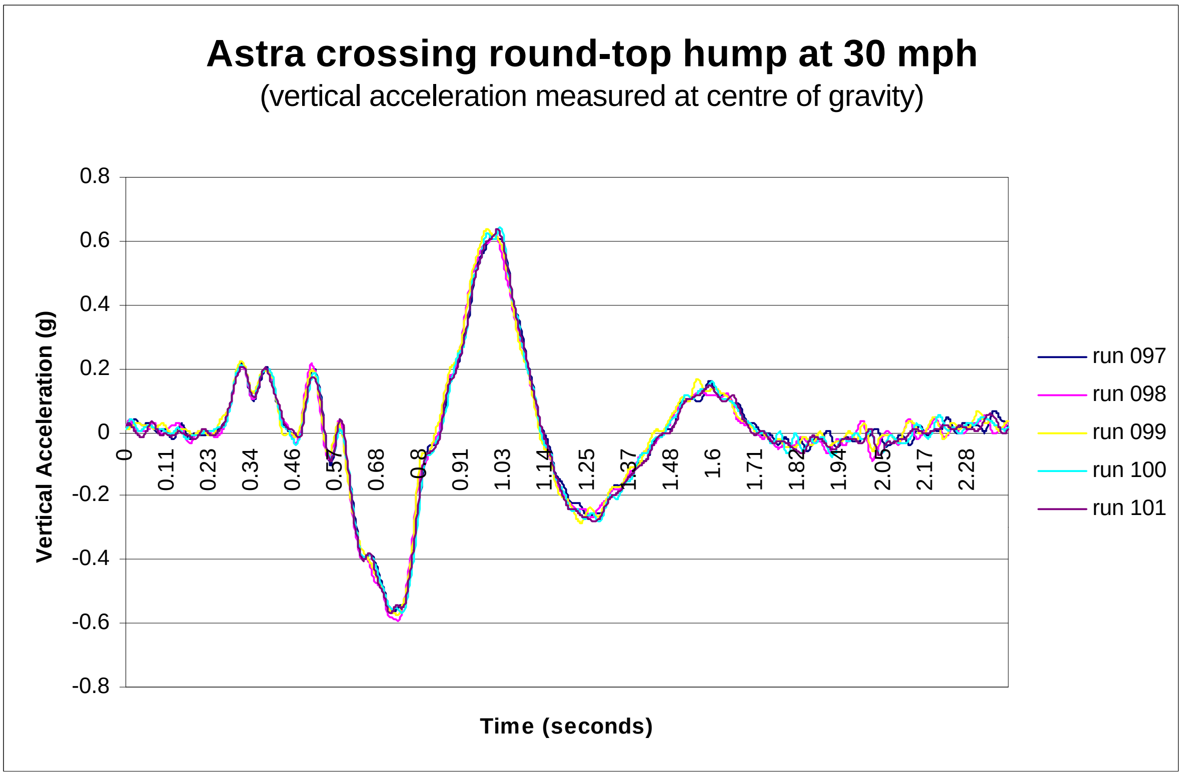

Figure 10 Physical test data for the COG vertical acceleration of the Astra

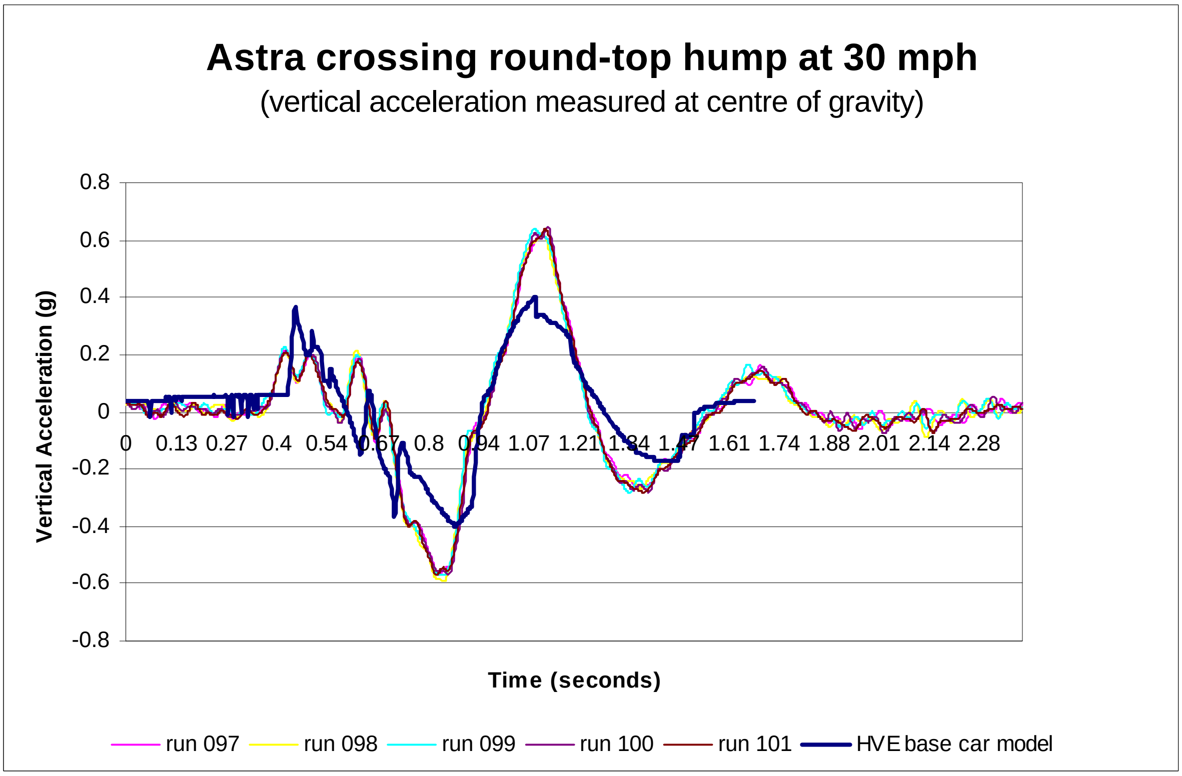

Figure 11 Comparison of physical, and initial simulation, test results for the COG vertical acceleration of the Astra

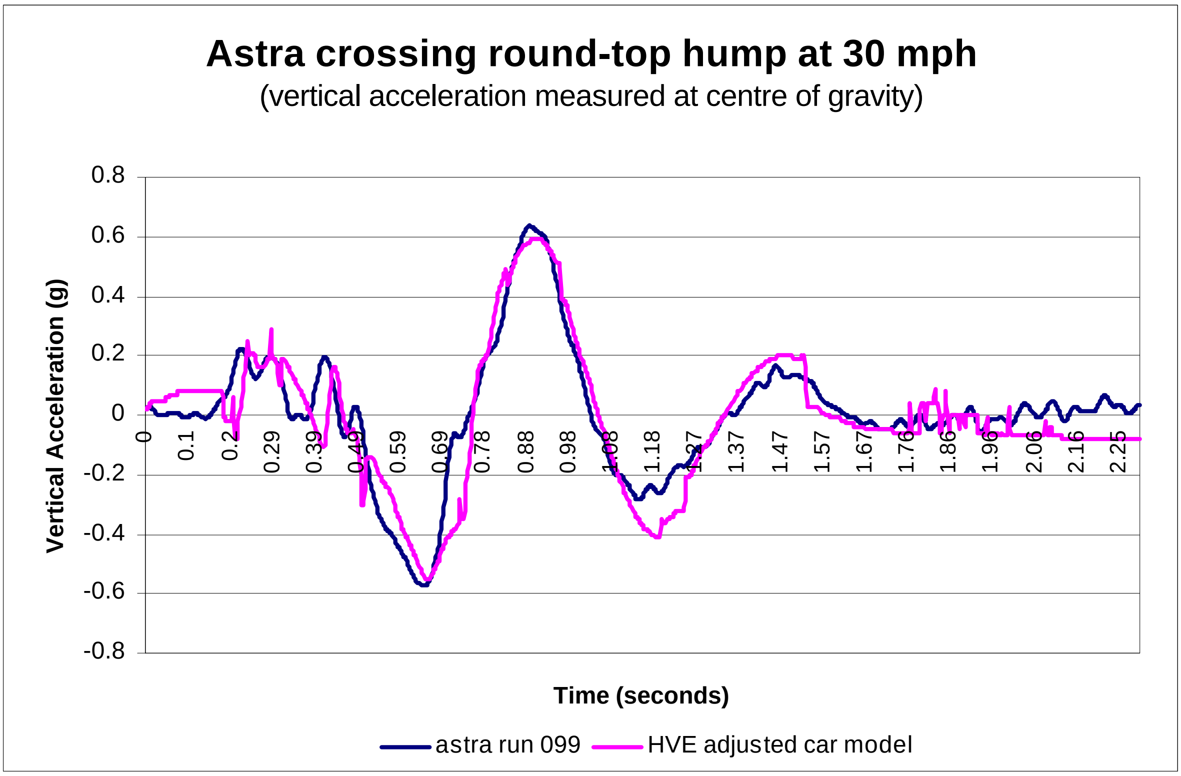

Figure 12 Comparison of physical, and 'best fit' simulation, test results for the COG vertical acceleration of the Astra (note: Pearson's correlation coefficient = 0.93, see Table 3)

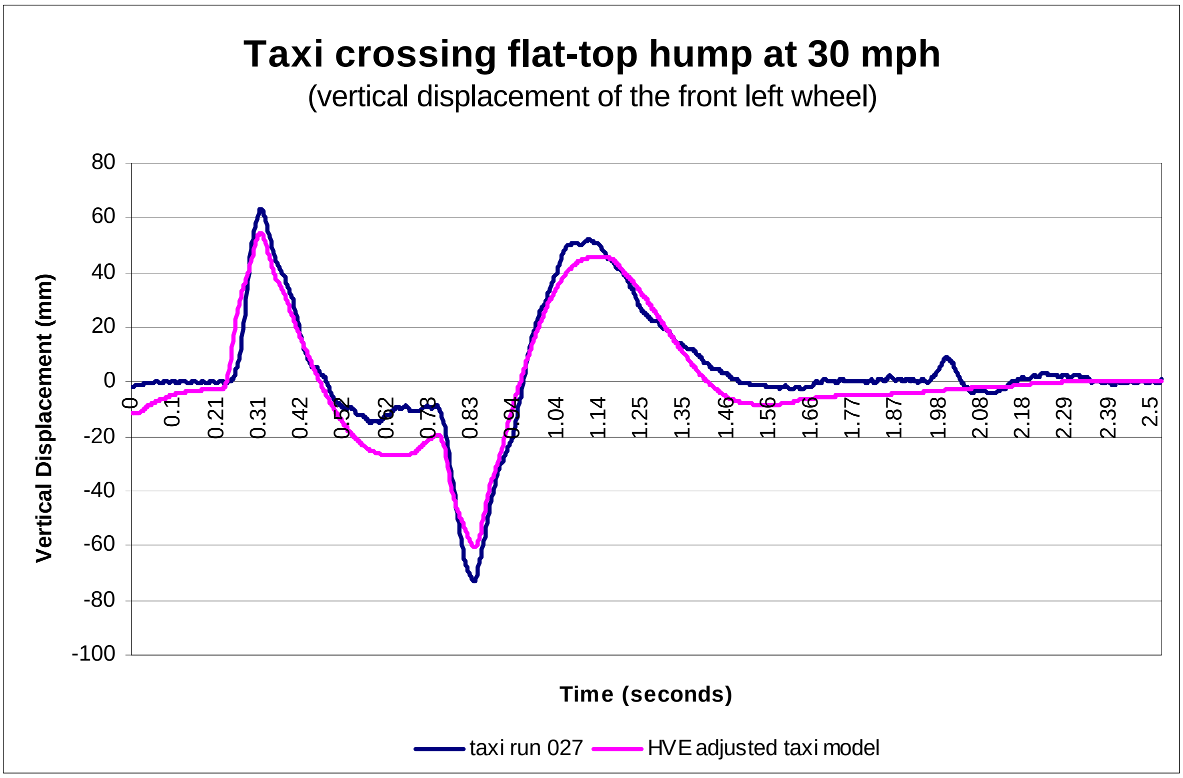

Figure 13 Comparison of physical, and 'best fit' simulation, test data for the vertical displacement of front left wheel of the taxi

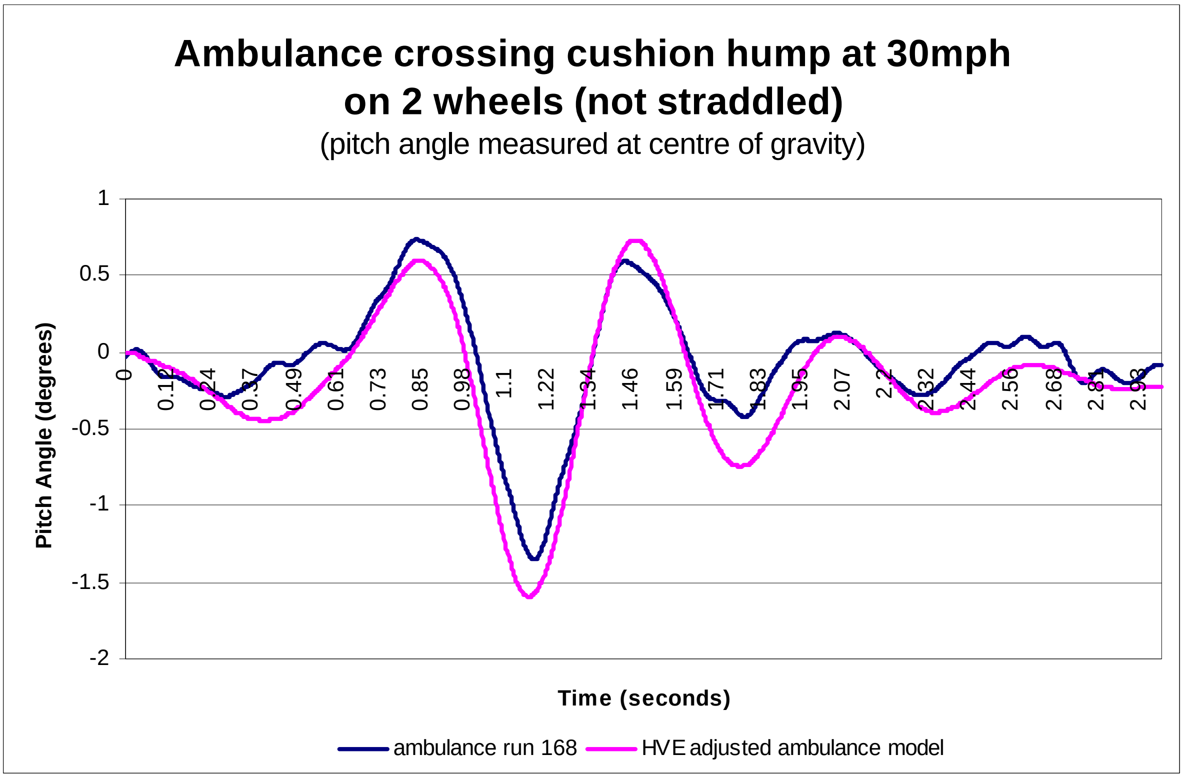

Figure 14 Comparison of physical, and 'best fit' simulation, test data for the pitch angle of the ambulance

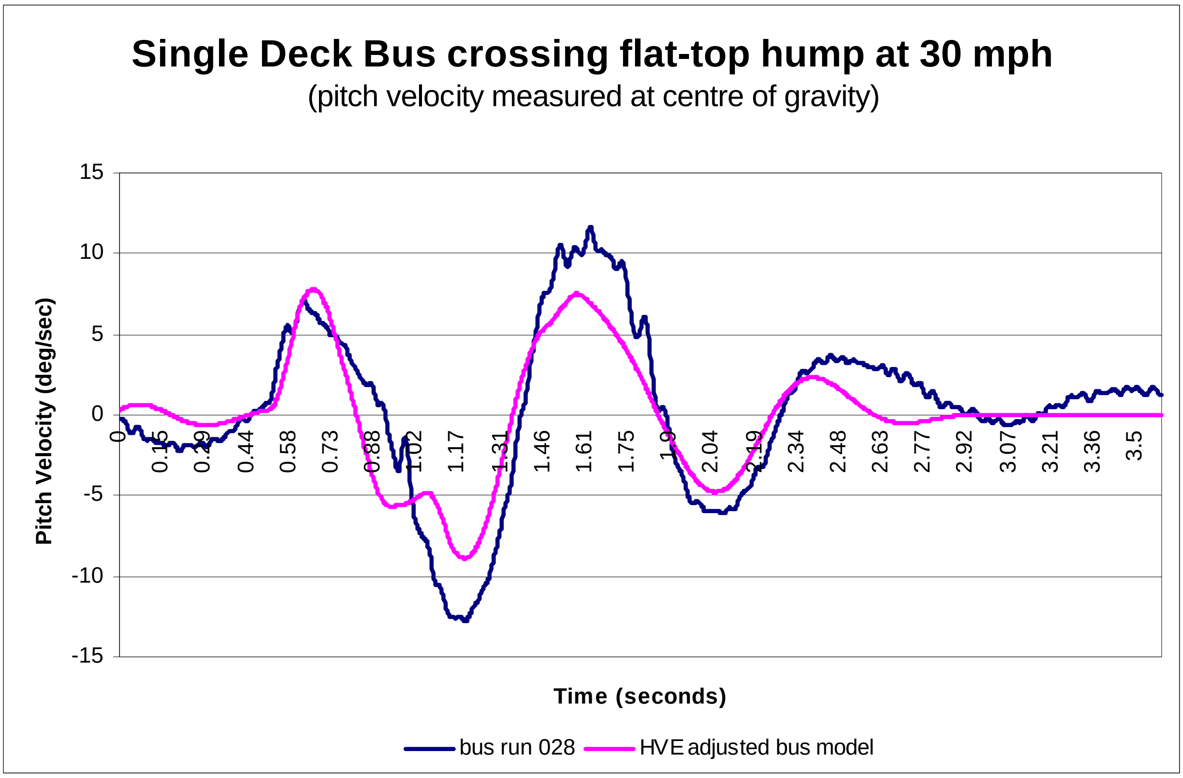

Figure 15 Comparison of physical, and 'best fit' simulation, test data for the pitch velocity of the single deck bus

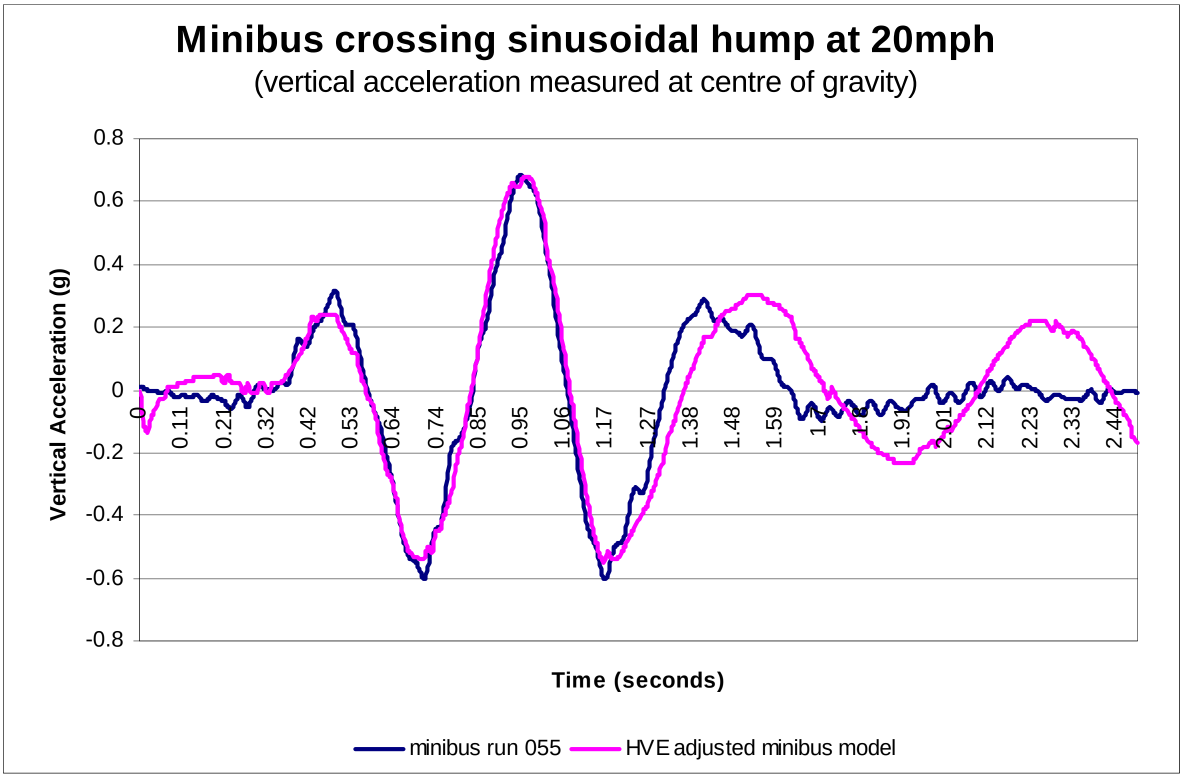

Figure 16 Comparison of physical, and 'best fit' simulation, test data for the COG vertical acceleration of the minibus (note: Pearson's correlation coefficient = 0.90 (0.95), see Table 3)

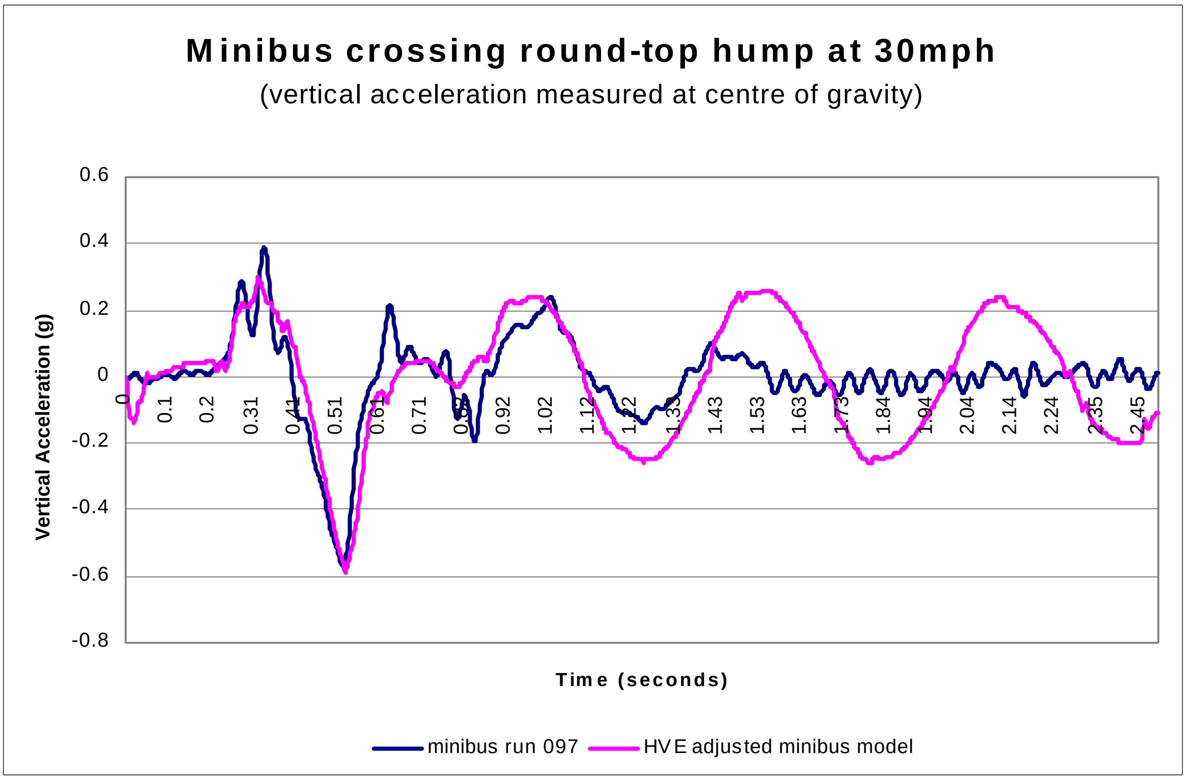

Figure 17 Comparison of physical, and 'best fit' simulation, test data for the COG vertical acceleration of the minibus (note: Pearson's correlation coefficient = 0.69 (0.82), see Table 3)

In order to investigate the relationship between the physical and simulation test data in depth, simulations were initially conducted using the simulated Astra vehicle, travelling over the round-top hump at 30 mph. The set up of the vehicle in this case used the vehicle geometry and suspension parameters as measured by Millbrook.

It was noted that the peak levels of COG vertical acceleration and pitch angle/rate calculated by SIMON were lower than the physical test data. Figure 11 shows this relationship for COG vertical acceleration. These initial tests also demonstrated that the pattern of COG vertical acceleration and pitch angle/rate simulation data was very consistent with that of the test data.

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

<u>Sensitivity Testing</u>

It was found that sensitivity tests of key variables allowed a ‘best fit’ between the simulation and physical test results to be developed.

A number of sensitivity tests were carried out for the Astra travelling at 30 mph over the round-top hump. These tests examined the effects of variations in several key simulation vehicle parameters, as follows:

- Spring rate - increased by as much as 30 to 40% on all wheels, or on the fronts/rears only;
- Damping rate - decreased by as much as 50% on all wheels, or on the fronts/rears only;
- Damping friction - decreased by as much as 50%;
- Pitch inertia - increased and decreased by 10%.

The sensitivity tests showed that, of the above vehicle properties, the spring rate and damping rate had the greatest effect on the simulation results.

The spring rate was the last vehicle property to be incorporated into the sensitivity tests because it was initially considered to be a parameter in which we could have confidence - given that it had been measured in a fairly standard manner during the physical testing phase.

As could be reasonably expected, the simulation test data was found to be quite sensitive to variations in the spring rate parameter. 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.

Damping friction values for the initial simulations were based on the default values for the Ford Escort two-door hatch (1991-1996) contained in the HVE vehicle database. Decreasing the damping friction by 50% had no significant effect on the simulation results.

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 vehicle, i.e. the Vauxhall Astra used by Millbrook, 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 that were examined had no significant effect on the simulation results.

No sensitivity analyses were performed on tyre variables.

<u>'Best Fit' Results</u>

A 'best fit' simulation for the Astra travelling over the round-top hump at 30 mph was achieved by adopting a 25% increase in the vehicle's spring rates and a 25% decrease in the damping rates, Figure 12. This scenario was adopted because it provided a good correlation between the simulation and physical test results based on a relatively straightforward manipulation of the vehicle's properties.

These modifications were adopted for all simulations involving the Astra and were found to provide good consistency between the simulation and physical test results.

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 Astra, i.e. a 25% increase in the vehicle's spring rates and a 25% decrease in the damping rates.

These modifications to the taxi vehicle model provided results that showed good consistency between the physical and simulation test results, Figure 13.

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 to be 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.

For further simulations with the ambulance vehicle model it was found that by adopting the measured suspension properties on the front axle and by increasing the spring rates by 15% and decreasing the damping rates by 25% on the rear axle the vehicle model provided good consistency between the physical and simulation test results, Figure 14.

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 Astra analyses, i.e. a 25% increase in the vehicle's spring rates and a 25% decrease in the damping rates. The simulated vertical accelerations that were observed based on these modifications were well below the peak levels shown in the physical test results.

Extensive variations of the spring and damping rates were examined for both axles, separately and in tandem. It was found that some combinations improved the correlation between the physical and test data, however, these 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.

A 'best fit' case for the single deck bus was achieved using the following modifications, the results of these modifications are shown in Figure 15;

- Front axle - spring rates increased by 200%, damping rates decreased by 40%;
- Rear axle - spring rates increased by 5%, damping rates decreased by 25%.

Additional sensitivity analyses were conducted to examine the effect of the inertial properties of the bus. These simulations involved increasing and decreasing the pitch inertia by 10%. The results 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.

The initial testing for the Minibus followed a similar approach to that adopted for the ambulance. These tests involved increases and decreases of around 25% to spring and damper rates, respectively. The 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 cased prolonged bounce of the rear suspension after travel over the hump, Figure 16.

Statistical Analysis

The statistical agreement between the physical test data and the simulation data for COG vertical acceleration, for each vehicle over each hump, was examined using a Pearson's Correlation Coefficient (r). This statistical procedure provides an indication of the strength and direction of the relationship between two sets of data. The results of these analyses are summarised in Table 3.

This procedure yields a single number that ranges between -1.00 and 1.00. The closer the absolute value of 'r' is to 1.00, the stronger the relationship. The closer the absolute value is to 0.00 the weaker the relationship.

A value of +1.00 signifies a perfect positive relationship, while a value of -1.00 indicates a perfect inverse relationship. The sign does not affect the strength of association; rather it simply indicates the direction in which the variables change in relation to each other.

The following ranges can be used as a general guide to the strength of correlation between two sets of data as defined by the absolute value of the correlation coefficient:

- 0.80-1.00 Strong Association;
- 0.60-0.79 Strong-Moderate Association;
- 0.40-0.59 Weak-Moderate Association;
- 0.30-0.39 Strong-Weak Association;
- 0.20-0.29 Weak-Weak Association;
- 0.00-0.19 Little, if any association.

Table 3 Pearson's Correlation Coefficients for Vertical Acceleration

Medium Saloon Car				
Vehicle Speed	**Round-top hump**	**Flat-top hump**	**Sinusoidal hump**	**Speed cushion (not straddling)**
10 mph	**0.85**	0.78	**0.88**	0.60
20 mph	**0.91**	**0.92**	**0.88**	**0.86**
30 mph	**0.93**	**0.86**	**0.90**	0.74
London Taxi				
Vehicle Speed	**Round-top hump**	**Flat-top hump**	**Sinusoidal hump**	**Speed cushion (not straddling)**
10 mph	0.61	0.29 **(0.82)**	**0.88**	0.42
20 mph	**0.82**	0.75	**0.82**	0.52
30 mph	**0.90**	**0.90**	**0.92**	0.71
Ambulance				
Vehicle Speed	**Round-top hump**	**Flat-top hump**	**Sinusoidal hump**	**Speed cushion (not straddling)**
10 mph	**0.83**	**0.84**	**0.92**	0.71
20 mph	0.66	**0.88**	**0.90**	**0.81**
30 mph	0.64	**0.87**	**0.90**	0.57
Single Deck Bus				
Vehicle Speed	**Round-top hump**	**Flat-top hump**	**Sinusoidal hump**	**Speed cushion (not straddling)**
10 mph	0.79	0.70	0.73	0.60
20 mph	0.58 (0.72)	0.59 (0.70)	0.58	0.35
30 mph	0.69	0.76	**0.80**	0.41
Minibus				
Vehicle Speed	**Round-top hump**	**Flat-top hump**	**Sinusoidal hump**	**Speed cushion (not straddling)**
10 mph	0.67	0.69	**0.87**	0.48
20 mph	**0.86 (0.95)**	**0.83 (0.93)**	**0.90 (0.95)**	0.74
30 mph	0.69 **(0.82)**	0.75 **(0.81)**	**0.81 (0.92)**	0.53

The Pearson's correlation between the physical test data and the simulation test data for the Vauxhall Astra travelling over the round top hump at 30 mph (as shown in Figure 12) provided a coefficient of 0.93. The Pearson's coefficients for the vertical acceleration data shown in Figures 16 and 17, were 0.90 and 0.69 respectively.

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 (rather than during the post-hump damping). The correlation coefficients for the portion of the data when the vehicle was in contact with the humps (in the case of the data presented in Figures 16 and 17) provide higher values, at 0.95 and 0.82 respectively.

In the course of this research it has been 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 simulation data for the 'best fit' simulations for all vehicles were most consistent with the test data during the period in which the vehicle was travelling over (i.e. in contact with) the road hump.

In several cases, it was found that slight re-alignment of the 'match' between a set of physical and simulation data could provide significantly different correlation coefficient values. In all cases the fit between the data has been optimised to achieve the highest correlation values.

Values in bold are those where the correlation coefficient can be regarded as showing a strong association between the data.

Table 3 presents the results of the Pearson's Correlation for all vehicles travelling over each hump at speeds of 10, 20 and 30 mph. The correlation values in Table 3 represent values for the whole data profile, i.e. all physical and simulation test data from first contact with the hump, until the completion of damping in the physical test data. Values in brackets relate to data from the period in which the vehicle was in contact with the hump only, i.e. does not include the period in which the suspension settled after travel over the hump. Where only one value is provided in Table 3 the physical test data and simulation test data profiles 'settle' at around the same point.

Using the taxi as an example, a particularly large variation can be seen for the vehicle travelling over the flat-top hump at 10 mph. In this case, the vertical acceleration data provides a relatively good match with the test data when the vehicle is in contact with the hump. However, the post hump damping phase is less consistent.

The correlation between the physical and simulation test data for the taxi travelling over both the round-top and flat-top humps at 20 mph improves, although the peak vertical acceleration values are slightly higher than the physical test data. A good match was provided by the taxi vehicle model over all humps at 30 mph.

During the contact phase between vehicles and the road humps the simulation data was 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.

More significant discrepancies occurred after the vehicles had travelled over the humps. This effect was particularly evident in the minibus simulations, and is demonstrated by the difference in the bracketed and un-bracketed correlation coefficients.

In the case of the minibus, these discrepancies are explained by the change in the suspension parameters that were required to develop the 'best fit' between data sets 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 16 and 17).

In general, the Astra, taxi and ambulance provided results with the best fit between the physical and simulation data for each hump. However the speed cushion provided the poorest correlation values for all vehicles.

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 the overall low correlation coefficients for these analyses.

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).

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.

This research demonstrates the importance of sensitivity analyses when simulating vehicle movements, and provides a guide as to the magnitude of variations in such analyses.

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 recognised that this research has focused on matching simulation results with physical test results for specific vehicle types. It is considered quite likely that other vehicles, for example, other medium sized family cars, would provide slightly different physical test results even if the physical characteristics of these vehicles were relatively consistent with those of the Astra. Thus, individual vehicles may require differing magnitudes of variation in suspension parametres to generate 'best fit' simulations.

Conclusions

The results of the research that form the basis of this paper constitute a body of data which will provide a basis for the development of virtual testing techniques using SIMON. Virtual testing using SIMON will assist in the future design of road humps in the UK by providing a valid, rapid and cost effective alternative to physical testing.

The fundamental pattern of the COG vertical acceleration data obtained from the simulation tests (in the majority of cases) closely match those obtained from the physical testing. Similarly, the simulation data obtained for other key parameters such as wheel vertical displacement, pitch angle and pitch rate matched the measured physical test data.

It was found that by conducting sensitivity analyses on the simulation data very good agreements could be created between physical test data and simulation test data in terms of both the pattern of the data, and the magnitude of the results.

Certain vehicle types, and road hump types, provided a better correlation between physical and simulation test data. In general, the Astra, taxi and ambulance provided simulation results that most closely matched the test data (after a 'best fit' vehicle model was developed for each).

The single deck bus provided results that were less consistent with the physical test data. It was considered that the front and rear air suspension of this vehicle was less suitable for simulation using SIMON than those of other test vehicles.

The minibus provided good results whilst the vehicle was travelling over the hump. However, it was considered that the changes made to the minibus vehicle model in HVE caused the movement of the vehicle after travelling over the humps to be less consistent with the physical test data.

In the authors' view, further analysis of the body of data developed as part of this research will provide the basis for a detailed validation study of the SIMON model. Any further validation work would benefit from additional physical testing of other vehicle types, in particular other cars and four wheel drive vehicles.

References

1. MacInnis, D. D., Cliff, W. E., and Ising, K. W., (1997), *A Comparison of Moment of Inertia Estimation Techniques for Vehicle Dynamics Simulation*. SAE Paper 970951.

2. Day, T. D., Roberts, S. G., and York, A. R., (2001), *SIMON: A New Vehicle Simulation Model for Vehicle Design and Safety Research*. SAE Paper 2001-01-0503.

3. Day, T. D., (1995), *An Overview of the HVE Vehicle Model.* SAE Paper 950308.

4. Garvey, J. T., (2000), Building Vehicles for HVE. WP#2000-6, Engineering Dynamics Corporation.