Improving the accuracy of weigh-in-motion systems

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This paper considers the design of, and initial results from, a multiple-sensor weigh-in-motion system installed in a public highway. The use of the multiple-sensor array resulted in a significant improvement in accuracy compared with existing two-sensor piezo WIM systems. There were indications that the accuracy of multiple-sensor arrays may depend partly on the spacing of the sensors and partly on the position of the individual sensors in the road.

1 INTRODUCTION

Weigh-in-motion (WIM) is the process of weighing fast moving vehicles using road mounted sensors. The instantaneous 'dynamic' wheel weights of vehicles can be used to estimate their static axle and gross weights.

Accurate and reliable estimates of static axle weights would be of considerable benefit in traffic monitoring. Uses such as pre-selection for enforcement weighing (1) have been limited by the unsatisfactory accuracy and reliability of the present systems.

Current WIM systems use only two sensors, primarily in order to measure the speed of the vehicle (which is required when calculating the instantaneous axle load on narrow sensors). The accuracy of these systems has been limited by the dynamic bouncing of axles at speed. The use of multiple-sensor WIM arrays should improve accuracy by averaging a number of instantaneous weights.

Initial trials of a prototype nine-sensor WIM array were conducted on the TRL research track in 1988 (2). Similar work, including modelling the responses of arrays and tests on a research track, has been conducted by Cambridge University (3). In both cases the arrays were evaluated using repeated passes of a limited number of vehicles. In order to evaluate WIM systems in representative conditions trials have to be conducted on a public highway using a large variety of vehicles. This paper describes the design, installation and evaluation of a multiple-sensor array in a public highway.

2 WIM TECHNOLOGY

WIM sensors have been in use for over 30 years. Early designs, such as the TRL Weighscale (4), used large metal plates which supported the entire wheel load for a short period. The instantaneous wheel weights were normally measured using strain gauges or load cells.

More recently narrow slot-mounted strip sensors have been developed. Only a small part of the wheel load is on the sensor at any one instant so the sensor output is usually integrated with respect to distance along the tyre contact patch. Compared with earlier sensors they are less expensive, easier to install and cause less disturbance to the road profile.

Piezo-electric strip sensors were developed in the early 1980's (5). When compressed the piezo-electric material produces an electrical charge which can be related to the force applied. A new capacitive strip sensor was developed in the mid 1980's (3). It consists of a hollow aluminium extrusion with an insulated inner copper electrode. When the sensor is compressed the capacitance between the extrusion and electrode changes in proportion to the load. This type of sensor was used in the multiple-sensor array installed in the public highway at Abingdon in Oxfordshire.

3 ACCURACY OF EXISTING EQUIPMENT

3.1 Measures of WIM accuracy

Two main measures of WIM accuracy are used in this paper:

MIF - the mean impact factor;
CoV - the coefficient of variation of the impact factor.

The weights recorded by WIM systems are compared with the equivalent 'static' weights measured using either an enforcement weighbridge or portable weighpads (the 'true' weights). The ratio of a WIM weight to the 'true' weight is defined as the impact factor. The mean impact factor (MIF) for a large number of vehicles provides an indication of systematic error. Ideally the mean impact factor would be 1.00.

The coefficient of variation (CoV) is a measure of the variability of the impact factors:

$$\text{CoV} = \frac{(\text{standard deviation of IFs}) \times 100\ \%}{\text{MIF}}$$

An additional measure of WIM accuracy is the wear factor ratio. Road wear is assumed to be proportional to the fourth power of the static axle weight (6) and is measured in terms of 'standard axles' where:

$$\text{road wear factor} = \left(\frac{\text{static axle weight (tonnes)}}{\text{standard axle weight}}\right)^4$$

In this paper the 'standard axle' is defined to have a static weight of 10 tonnes. The wear factor ratio is the ratio of the road wear factor calculated using the WIM weights to the 'true' road wear factor.

3.2 Accuracy of typical piezo WIM systems

In 1990/91 TRL conducted 8 surveys at four WIM pre-selection sites (1). At each site the outputs from two piezo-electric strip sensors were averaged. The main results from the 8 surveys were:

MIF (vehicles)	0.93 - 1.18 *
CoV (vehicles)	12 - 32 per cent
CoV (axles)	18 - 34 per cent
Wear factor ratio	0.67 - 2.06

(* for one survey the WIM system was uncalibrated and had an MIF of 1.31.)

Fuller results are given in Table 1.

Table 1. Accuracy of typical piezo WIM systems.

Survey	MIF *	CoV		Wear factor ratio	
		Veh.	Ax.	Original	Adjusted
Beattock Summit:					
Sept. 1990	1.18	16%	22%	1.76	0.87
Nov. 1990	0.93	14%	21%	0.70	0.87
Dunkirk:					
Sept. 1990	0.99	14%	19%	0.67	0.67
Nov. 1990	1.16	32%	34%	2.06	1.10
Jan. 1991	0.96	23%	26%	0.75	0.84
Sawtry:					
Sept. 1990	0.97	12%	18%	0.90	0.98
Nov. 1990	1.00	15%	27%	0.91	0.86
South Cave:					
Jan. 1991	1.31	16%	23%	1.74	0.54

* MIF for vehicle weights (system at South Cave had not been calibrated).
Original wear factor ratio = using unadjusted survey data.
Adjusted wear factor ratio = using data adjusted so that the MIF for axle weights equals 1.00.

4 DESIGN OF THE ARRAY

When designing a multiple-sensor array to estimate static weights a number of factors need to be taken into account. These include:

- number of sensors
- array length
- inter-sensor spacing
- output processing
- traffic speed
- vehicle bounce characteristics

In 1990 TRL commissioned EASAMS Ltd to recommend array designs to cope with a variety of speeds and suspension types (7). They recommended array designs with variable inter-sensor spacings and unequal weightings on each sensor.

The designs were assessed by modelling their performance using wheel load data obtained from TRL instrumented vehicles with different suspensions, speeds and road roughnesses. The outputs from the array were calculated at each sensor location as the overall array was stepped systematically through the distance-based wheel load data in small increments. After each step the wheel loads at the sensor positions were used to provide an estimate of the static wheel weights. The CoVs of the resulting impact factors over all available data were used to compare the array designs.

This method was also used to design optimal arrays with equally spaced sensors by varying the array lengths and calculating the CoV at each new length. The array designs which showed the least variation (lowest CoV) in static wheel weight prediction were those best able to respond to the dominant frequencies in the suspension data.

The CoVs for these optimised arrays were no higher than those for the unequally spaced EASAMS designs with the same number of sensors and speeds between 20 and 60 mile/h. Table 2 shows the dimensions of the optimised equally spaced arrays.

Table 2. Optimised equally spaced arrays.

Number of sensors	Optimised equally spaced arrays	
	Spacing (m)	Length (m)
2	4.0	4.0
3	2.75	5.5
4	4.2	12.6
5	2.6	10.4
6	2.7	13.5
7	2.7	16.2
8	2.7	18.9
9	2.7	21.6
10	2.7	24.3
11	2.15	21.5
12	2.1	23.1
13	1.25	15.0
14	1.25	16.25
15	1.2	16.8
16	1.25	18.75

Array length was constrained to below 20 metres to reduce the likelihood of two vehicles being on the array simultaneously. The eight sensor design with an overall length of 18.9 metres and an inter-sensor spacing of 2.7 metres was selected for installation at Abingdon. This allowed the study of other arrays with a spacing of 2.7 metres (near the optimum for 3, 5, 6, 7 and 8 sensor arrays).

5 EVALUATION OF THE ARRAY

5.1 Experimental Site

The array was installed during September 1991 in the northbound slow lane of the A34 about 500 metres south of the interchange with the A415 at Abingdon. There is an enforcement weighbridge at the A34 / A415 junction.

5.2 The Weigh-in-Motion equipment

The capacitive sensors installed at Abingdon were 1.8 metres long and 27 mm wide. A pair of 'wheel' sensors was required to cover the width of the lane (forming an 'axle' sensor). The eight 'axle' sensors, with an inter-sensor spacing of 2.7 metres, were mounted in narrow slots cut in the road and sealed with epoxy resin.

The sensors were connected to a data logger which was linked to a laptop computer. For each wheel the computer recorded a list of sensor events consisting of the event time, the sensor number (1 to 16) and the raw sensor output. The sensor outputs were later multiplied by the vehicle speed and sensor calibration factor to give the instantaneous wheel weights. The recording of raw sensor data allowed different calibration factors and combinations of sensors to be examined.

5.3 Data collection at the enforcement sessions

Data were collected during enforcement sessions at the Abingdon weighbridge. The police normally selected vehicles for enforcement weighing at a disused slip road about 3 km south of the weighbridge. As the selected vehicles left the slip road a 'spotter' radioed their descriptions to the WIM operator. This enabled the vehicles to be correctly matched as they passed over the WIM on their way to the weighbridge.

5.4 Methods of Calibration

A number of different calibration methods were investigated.

5.4.1 Data from enforcement sessions

Calibration factors were calculated using the axle weights recorded by both the WIM and the weighbridge during the first two enforcement sessions. The weighbridge recorded axle weights rather than individual wheel weights and so the calibration factors were calculated assuming that the wheel load at each sensor was half the 'true' axle load.

5.4.2 Multiple passes of a single vehicle

Calibration factors were also calculated using repeated passes of a 17 tonne 2-axle rigid vehicle with known wheel weights (measured using portable weighpads). Factors were calculated for 14 passes of the vehicle at about 50 mile/h and 10 passes at less than 10 mile/h.

5.4.3 Instrumented Vehicle

In order to calibrate each of the sensors using the actual instantaneous wheel weights a vehicle with load measuring instrumentation was driven over the array a number of times. Factors were calculated for 6 passes of the vehicle at about 50 mile/h and 22 passes at less than 20 mile/h.

6 RESULTS

The following results are based on an initial analysis of data collected up to 7 April 1992.

6.1 Available data

Data are available for 12 enforcement sessions between 19 September 1991 and 7 April 1992 (see Table 3).

Table 3. Survey dates and data collected.

Survey Date	Complete Data		Sensor temp range (°C) *	Avg Speed (mile /h)
	Veh.	Ax.		
19/09/91	13	47	**	47.5
01/10/91	32	110	12-22	51.2
05/02/92	28	104	8-11	51.6
10/02/92	15	54	8-9	51.1
19/02/92	6	17	2-4	52.9
25/02/92	9	34	3-7	47.5
02/03/92	10	37	12-13	52.9
11/03/92	12	45	8-10	51.7
19/03/92	17	62	16-17	52.1
24/03/92	13	47	9-14	49.7
01/04/92	5	20	8-10	50.5
07/04/92	9	32	7-9	52.7
Total	169	609	3-22	51.1

* Surface temperature.
** No temperature data.

During these sessions 213 vehicles were matched. Of these only 169 had complete sensor data (16 sensor events per axle). Data were lost due to the inability of the data logger to cope with closely following multi-axled vehicles. Incoming sensor outputs took priority over the transfer of data to the computer resulting in a loss of the latter. Only complete data were used in the analysis.

6.2 Calibration Methods

The calibration factors obtained using each of the methods described in Section 5.4 were applied to the raw sensor data. The weights from the 8 sensors in a wheel track were averaged to provide an estimate of the static wheel weight. These were then summed to give axle and gross weights. The overall results are summarised in Table 4. The MIFs using the calibration based on the first two enforcement sessions were close to unity (0.99 for vehicles and 1.00 for axles). In comparison the other two methods of calibration (multiple passes of a vehicle of known static axle weights and of an instrumented vehicle) led to systematic

Table 4. Calibration Methods.

Calibration Method	Calibrated Array Performance	
	Vehicles MIF (CoV)	Axles MIF (CoV)
Data from enforcement sessions		
- first two sessions (19/9/91 and 1/10/91) 45 vehicles	0.99 (6.7)	1.00 (8.2)
Multiple passes of single vehicle		
- 14 passes of 2-axle rigid (12/12/91) 50 mile/h	1.06 (6.6)	1.07 (8.2)
- 10 passes of 2-axle rigid (25/3/92) less than 10 mile/h	1.08 (7.0)	1.09 (8.5)
Instrumented vehicle		
- 6 passes of 2-axle rigid (12/12/91) 50 mile/h	1.04 (6.7)	1.05 (8.3)
- 22 passes of 2-axle rigid (25/3/92) less than 20 mile/h	1.02 (7.0)	1.03 (8.5)

over-weighing (MIFs greater than 1.02).

The 8 sensor array was assessed using calibration factors based on data from the instrumented vehicle travelling at about 50 mile/h. These factors should reflect the true instantaneous loads imposed on the sensors.

6.3 Static axle and gross weight estimates

Table 5 shows the results for each of the 12 enforcement sessions.
The mean impact factor was stable at about 1.04±0.03 throughout the seven month period. The variation shows no consistent relationship with the temperature of the sensors.

Table 5. Array performance by enforcement session.

Survey Date	Vehicles		Axles	
	No.	MIF (CoV)	No.	MIF (CoV)
19/09/91	13	1.04 (4.4)	47	1.04 (6.3)
01/10/91	32	1.04 (5.5)	110	1.05 (7.1)
05/02/92	28	1.03 (10.3)	104	1.05 (10.7)
10/02/92	15	1.03 (4.8)	54	1.05 (7.3)
19/02/92	6	1.03 (4.1)	17	1.05 (7.2)
25/02/92	9	1.01 (9.6)	34	1.02 (11.1)
02/03/92	10	1.04 (6.6)	37	1.05 (7.4)
11/03/92	12	1.05 (7.1)	45	1.07 (8.0)
19/03/92	17	1.07 (4.6)	62	1.08 (6.3)
24/03/92	13	1.04 (5.3)	47	1.05 (7.7)
01/04/92	5	1.04 (10.0)	20	1.06 (13.5)
07/04/92	9	1.04 (3.2)	32	1.05 (4.8)
All	169	1.04 (6.7)	609	1.05 (8.3)

Table 6 shows array performance by axle weight. For axle weights greater than 3 tonnes the MIF was relatively stable (1.05-1.08). At lower weights the array appears to under-weigh (MIF 0.94-1.00).

Table 6. Array performance by axle weight.

Axle Weight band (tonnes)	Axles	
	Sample size	MIF (CoV)
up to 2.00	24	0.94 (12.7)
2.01 - 3.00	56	1.00 (9.5)
3.01 - 4.00	59	1.05 (7.3)
4.01 - 5.00	60	1.06 (10.0)
5.01 - 6.00	124	1.05 (6.8)
6.01 - 7.00	126	1.08 (6.9)
7.01 - 8.00	66	1.06 (8.2)
8.01 - 9.00	47	1.05 (7.1)
9.01 - 10.00	23	1.05 (6.2)
over 10.00	24	1.05 (5.0)
All	609	1.05 (8.3)

Array performance by class of vehicle is shown in Table 7.

Table 7. Array performance by class of vehicle.

Vehicle Class	Vehicles		Axles	
	No.	MIF (CoV)	No.	MIF (CoV)
2-axle rigid	63	1.02 (8.1)	126	1.02 (8.8)
3-axle rigid	6	1.04 (5.5)	18	1.05 (6.5)
4-axle rigid	5	1.05 (1.2)	20	1.07 (5.8)
3-axle artic	3	1.03 (5.7)	9	1.04 (6.5)
4-axle artic	31	1.03 (6.4)	124	1.03 (8.9)
5-axle artic	39	1.06 (5.3)	195	1.07 (7.8)
6-axle artic	13	1.10 (3.7)	78	1.10 (7.1)
4-axle drawbar	7	1.02 (2.1)	28	1.02 (5.3)
Other*	2	1.06 (6.5)	11	1.06 (7.6)
All	169	1.04 (6.7)	609	1.05 (8.3)

* 5-axle drawbar and 6-axle artic (4+2)

Generally the MIFs and CoVs were consistent between classes of vehicle (MIF 1.03 - 1.07). However the MIF for 2-axle rigids was relatively low (1.02) and the MIF for 6-axle artics was relatively high (1.10).

6.4 Accuracy versus the number of sensors

The eight 'axle' sensors were labelled 1 to 8 and all possible combinations were used to assess the relationship between the CoV for axles and the number of sensors in the array. A total of 255 combinations were assessed including the complete array. Thus, for a given number of sensors, the CoV could vary substantially, depending on which of the 8 sensors were used in the reduced array. Figure 1 shows the maximum, minimum and mean CoV for each number of sensors.

There was a large range in the axle CoVs for the individual axle sensors (11.6 per cent for sensor 2 to 23.2 per cent CoV for sensor 4). This may reflect the variability of axle loads at these sensor positions. It was noted that the variability was different for multiple runs using the same vehicle at slower speeds (during the slow speed calibration runs in March 1992 the axle CoVs ranged between 6.4 per cent for sensor 8 to 12.6 per cent for sensor 3).

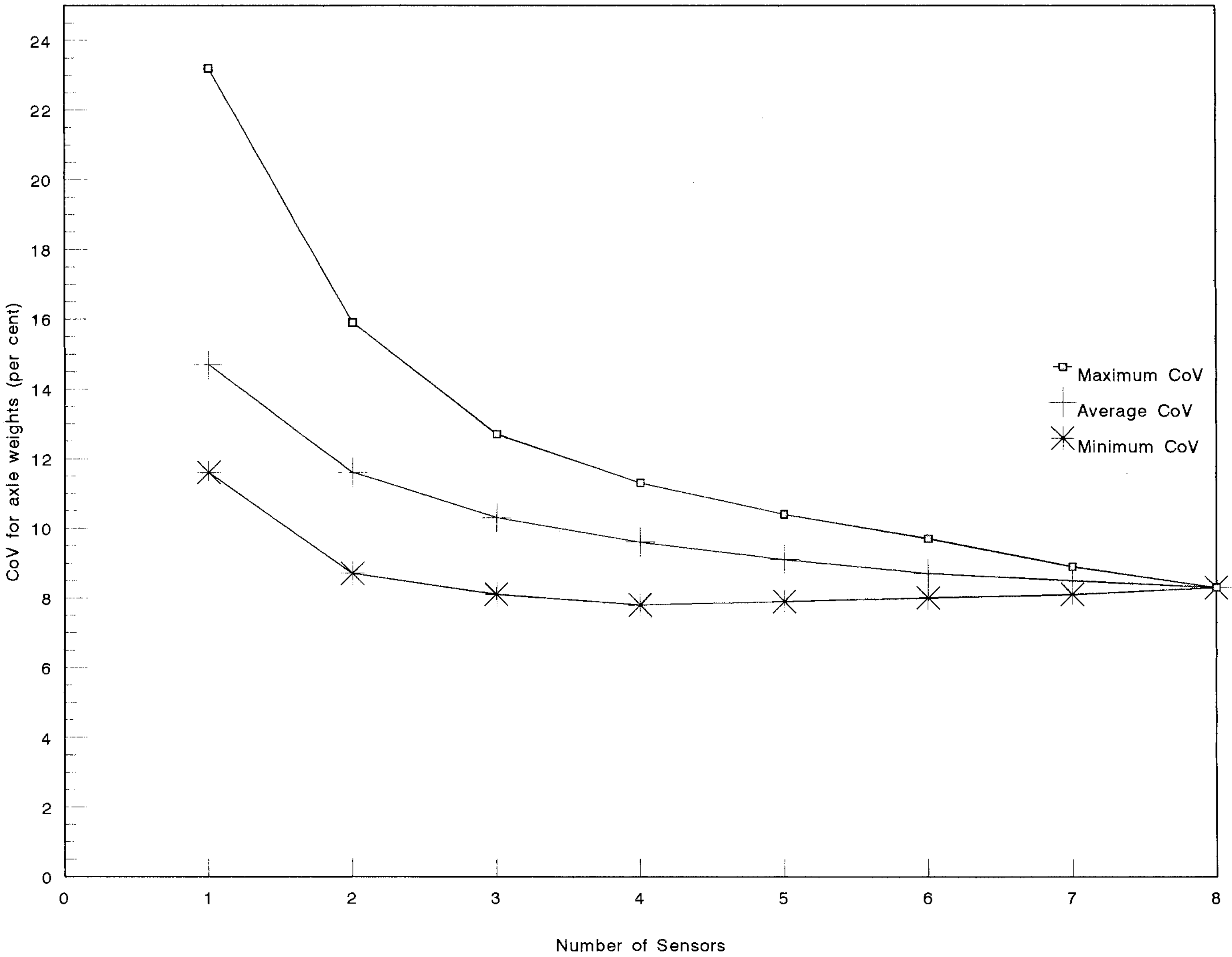

Fig. 1. The relationship between coefficient of variation and number of sensors.

As expected, the range of CoVs decreased with increasing number of sensors. For example, the axle CoVs for four sensor arrays varied between 7.8 per cent and 11.5 per cent. However the minimum CoV for arrays with 3 or more sensors was relatively stable at about 8 per cent. The four sensor combination of 1, 2, 5 and 8 had the lowest overall CoV of 7.8 per cent. There is no reason to suppose that it will be possible to arrange a four-sensor array in an optimum arrangement on any given road, so it is likely that, overall, the performance will improve as more sensors are used.

6.5 Wear factor ratios

In Table 8 road wear factors calculated using the 8 sensor WIM array are compared with the road wear factors calculated from the enforcement weighbridge weights. The wear factor ratios were mainly in the range 1.11 to 1.20. The exceptions were for 6-axle artics (1.41) and 'others' (1.30). The consistent over-estimation by the WIM was mainly due to the MIF of 1.05 for axle weights and would be largely corrected by dividing the WIM road wear factors by 1.05^4 (1.22).

Table 8. Road Wear (in standard axles) by class of vehicle.

Vehicle Class	Number of axles	Road wear (standard axles) calculated using		Wear factor ratio (WIM/ weigh-bridge)
		Enforcement weighbridge	WIM	
2-axle rigid	126	9.7	11.7	1.20
3-axle rigid	18	6.8	8.0	1.18
4-axle rigid	20	5.5	6.3	1.14
3-axle artic	9	1.8	2.0	1.13
4-axle artic	124	16.8	19.1	1.14
5-axle artic	195	52.2	62.0	1.19
6-axle artic	78	12.2	17.2	1.41
4-axle drawbar	28	5.3	5.9	1.11
Other*	11	0.6	0.8	1.30
All	609	110.8	132.9	1.20

* 5-axle drawbar and 6-axle artic (4+2)

7 DISCUSSION

7.1 Calibration

None of the calibration methods was totally satisfactory. The method using data collected during enforcement sessions gave MIFs close to unity. These data however, were not independent of the main data (they formed 27 per cent of the data used in the analysis). The other methods resulted in systematic over-weighing of vehicles (MIFs greater than 1.02). Further analysis and runs with instrumented vehicles are planned.

7.2 Eight sensor array

The MIFs for the twelve enforcement sessions were very stable with no indication of drift over time.

The array under-weighed axles less than 3 tonnes. The array performance would have been improved by disregarding light axles or by introducing non-linear calibration factors. Most light axles occurred on 2-axle rigid vehicles which may explain the low average impact factors for that class. The other classes of vehicle were weighed relatively consistently although the array tended to slightly over-weigh the 6-axle artics.

There was no observed temperature dependence of the sensors during the trials (sensor surface temperature range 3°C to 22°C). Speed dependency could not be investigated because of the narrow range of speeds at the site.

7.3 Reduced arrays

It appears that the CoVs for arrays of sensors depends partly on the spacing of the sensors and partly on the CoVs for the individual sensors. It is planned to study the road profile at the Abingdon site in order to establish whether there is a relationship between the road profile and the CoV for individual sensors. In addition, further runs with instrumented vehicles should provide information about sensor accuracy.

8 CONCLUSIONS

Following a preliminary analysis of the results from the 8 sensor array installed at Abingdon, the following conclusions have been drawn.

1. The eight sensor array performed significantly better than existing 2 sensor piezo WIM systems. The coefficients of variation were 6.7 per cent for vehicles and 8.3 per cent for axles. This compares with, at best, 12 per cent for vehicles and 18 per cent for axles observed during TRL trials of piezo-electric WIMs during 1990/91.

2. No drift in mean impact factors was observed but there was a tendency for the 8 sensor array to under-weigh light axles (less than 3 tonne).

3. The overall wear factor ratio was 1.20. This was mainly due to the mean impact factor of 1.05 for axles and would be largely corrected by dividing the WIM road wear factors by 1.05^4 (1.22).

4. The accuracy of a multiple-sensor array appears to depend partly on the spacing of the sensors and partly on the position of the individual sensors in the road.

5. Increasing the number of sensors not only improves the ability of the array to sample a wheel load profile but also reduces the influence of individual sensors with high CoVs.

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