Accuracy of Weigh-in-Motion Scales and Piezoelectric Cables

A. T. Papagiannakis, W. A. Phang, J. H. F. Woodrooffe,
A. T. Bergan, and R. C. G. Haas

This paper describes an experimental study comparing the accuracy of Weigh-in-Motion (WIM) scales and piezoelectric cables (PIEZO). The axle loads measured by the WIM and the PIEZO are compared to the dynamic axle load measurements obtained with the instrumented vehicle developed by the Vehicle Dynamics Lab of the National Research Council of Canada. The experiment was carried out in October 1987 at the instrumented pavement site constructed by the Ministry of Transportation of Ontario on Highway 7N north of Toronto. The site is equipped with a variety of sensors, including one conventional, platform-type WIM scale and five piezoelectric sensors. The experiment involved three levels of vehicle speed (40, 60, and 80 km/h), two levels of tire inflation pressure (80 and 100 psi), and two suspension types (air and rubber). Three replicate runs were performed for each combination of variables. The longitudinal placement of the vehicle with respect to the sensors was determined with a laser beam-based axle detector. Analysis of the accuracy of individual sensors revealed that only two of the PIEZO cables were sensitive with respect to tire inflation pressure, while none was sensitive with respect to vehicle speed. The average accuracy of the WIM scale was in the order of 6 percent, while the accuracy of the PIEZO cables ranged from 6 to 12 percent. Paired comparisons of the accuracy of each of the PIEZO cables to the accuracy of the WIM scale revealed that one of the PIEZO cables is comparable to the WIM scale while the other four are less accurate than the WIM scale. Considering the variation involved, however, only one of the PIEZO cables was shown to be significantly less accurate than the WIM scale.

The accuracy of systems weighing vehicles in motion has been a subject of debate since their conception in the early 1950s (*1*). This is mainly because the meaning of "accuracy" has not been properly recognized as "the closeness or nearness of the measurements to the true or actual value of the quantity measured" (*2*, p. 14). Typically, experimental studies have compared scale measurements to the static axle loads of passing vehicles. Findings of recent studies, however, suggest that the axle loads of moving vehicles can be considerably different from their static values (*3–6*). It was shown, for example, that the coefficient of variation of dynamic load ranges from 4 to 20 percent, depending on suspension type, vehicle speed, and level of pavement roughness (*6*). An example of the variation in time of the axle load generated by a leaf-spring suspension is shown in Figure 1, suggesting a frequency of load fluctuation of approximately 3 cycles/sec. Obviously, the "true" dynamic axle load can be considerably different than the static one at any time. Therefore, evaluating the accuracy of weigh-in-motion scales on the basis of static axle loads is conceptually wrong and confuses rather than resolves the problem.

To date, most of the experience with weigh-in-motion scales has been with transducer-based scales (*7, 8*). Recently, there has been a growing interest in the development of piezoelectric sensors as an alternative to the conventional weigh-in-motion scales (*9*). Piezoelectric cables are made of a piezoelectric ceramic material wrapped around a conductive core and covered by a 3-mm-diameter outer sheath. Cables are placed flush with the pavement using a steel channel filled with resin. The cables produce a voltage proportional to the stress level applied and can be calibrated to yield axle load.

The considerably different operational and cost characteristics of conventional weigh-in-motion scales and piezoelectric cables suggest the need for a thorough comparison of their accuracy. This paper addresses this problem by comparing the measurements of these two types of weigh sensors, hereafter referred to as WIM and PIEZO, respectively, to the "true" dynamic axle load obtained with an instrumented vehicle. This vehicle was developed by the National Research Council of Canada (NRCC) for the Roads and Transportation Association of Canada Weights and Dimensions Study (*4, 5*), (Figure 2). The study was undertaken jointly by the Ministry of Transportation of Ontario (MTO) and the Vehicle Dynamics Laboratory of the NRCC. The experiment was conducted at the MTO instrumented pavement site on HW 7N north of Toronto. The MTO instrumented site is equipped with one WIM scale, five PIEZO sensors, and a variety of pavement response sensors (i.e., strain gauges, deflection transducers, and temperature transducers) (Figure 3). The pavement layer thicknesses at the site were measured at 9, 15.6, and 42.8 cm, respectively (i.e., 3.5, 6, and 16.7 in.). The WIM scale is placed on a Portland concrete pad that is typical of this type of installation. The PIEZO sensors were installed as part of a joint program between the MTO and the French Laboratoire Centrale des Ponts et Chaussées. This paper describes the particular objectives, discusses the testing methodology, and presents the results of the study.

A. T. Papagiannakis, Memorial University of Newfoundland, St. John's, Newfoundland A1B 3X5, Canada. W. A. Phang, Pavement Management Systems, 3729 Union Road, Buffalo, N.Y. 14225. J. H. F. Woodrooffe, National Research Council of Canada, 89 Uplands Road, Ottawa, Ontario K1A 0R6, Canada. A. T. Bergan, University of Saskatchewan, Saskatoon, Saskatchewan S7N 0W0, Canada. R. C. G. Haas, University of Waterloo, Waterloo, Ontario A1B 3X5, Canada.

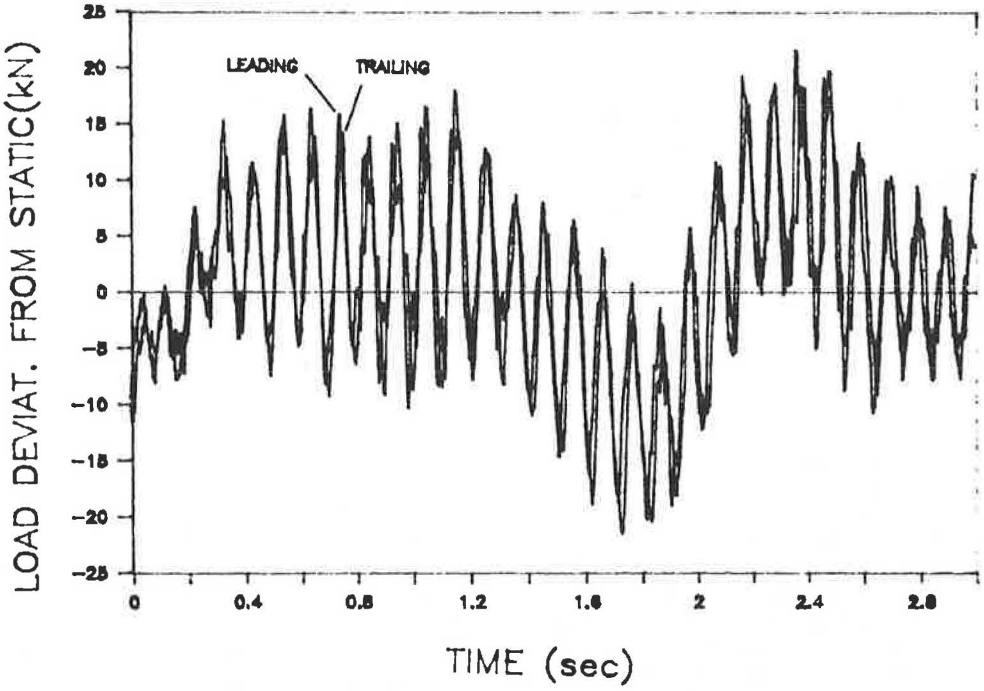

FIGURE 1 Dynamic axle loads of tandem axles on a leaf-spring suspension (*6*).

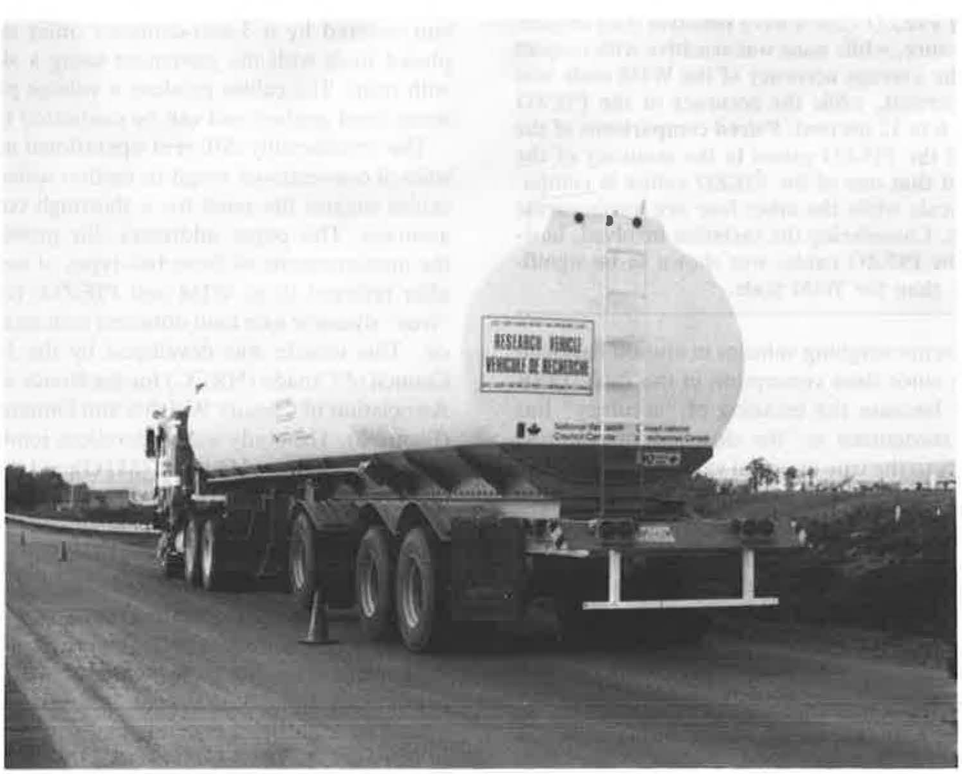

FIGURE 2 Instrumented vehicle developed by NRCC.

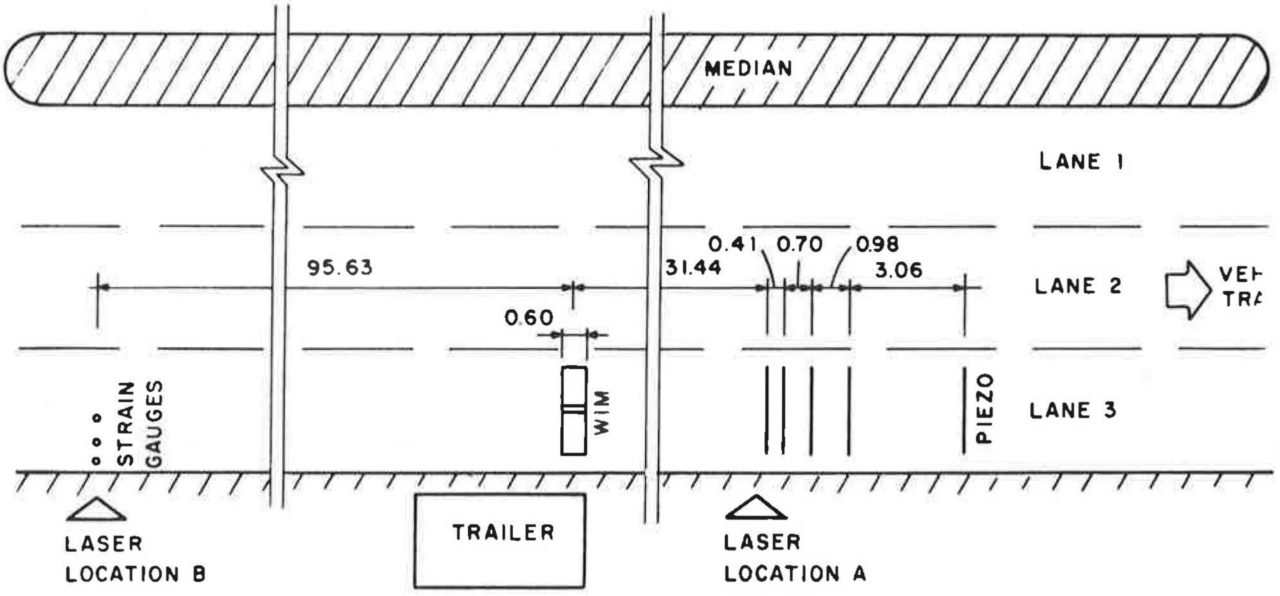

FIGURE 3 Arrangement of WIM and PIEZO sensors at MTO site (i.e., dimensions in meters).

OBJECTIVES

The particular objectives of the study are to

1. Determine the accuracy of WIM and PIEZO sensors under a variety of vehicle and operating conditions (e.g., tire inflation pressure, suspension type, vehicle speed) and
2. Compare the accuracy of each of the PIEZO sensors to the accuracy of the WIM scale over the range of independent variables.

THE EXPERIMENT

The NRCC vehicle was equipped with an air suspension on the drive axles and a rubber suspension on the trailer axles. Study of their dynamic behavior has shown that the rubber suspension can produce considerably higher dynamic loads than the air suspension at high vehicle speeds and/or levels of pavement roughness (*4–6*). It was also shown that the dynamic axle load generated by the right-hand side and the left-hand side of an axle can be substantially different because of vehicle roll and pavement cross slope. On the other hand, for relatively smooth pavements, the inertial load component generated by the acceleration of the tire assemblies is not substantial and can be neglected.

Although the pavement roughness at the MTO site was moderate (Table 1), it was decided to monitor only the right-hand and left-hand strain gauges on each axle of the NRCC vehicle (Table 2). The accelerometers could not be monitored because of the limited number of channels in the data recording system. The output of all the gauges was recorded on an analogue FM tape that was subsequently digitized using a frequency of 100 cycles/sec. The static load of each axle was added to the measured deviation to yield the total dynamic axle load. The static axle weights were obtained using a static weigh scale operated by the MTO for load enforcement purposes (Table 3). The lack of accuracy resulting from neglecting the inertial component of the axle load can be up to 5 percent, as reported by Woodrooffe et al. (*5*). On the other hand, the accuracy of the static weigh scale is in the order of 1 percent, as indicated by the gross vehicle weight measurements obtained for the two positions of the lift axle (Table 4). There is also the possibility that part of this discrepancy may be due to sloshing of the water ballast carried in the tank of the vehicle.

The most crucial aspect of the testing was to relate particular load values of the load output from the NRCC vehicle to sensor measurements on the ground. For this purpose, the longitudinal position and the speed of the NRCC vehicle should be known exactly. This was accomplished with a laser beam-based axle detector that transmitted a signal on the NRCC vehicle every time an axle interrupted the laser beam (*6*). The laser beam was placed across the driving lane directly above the first PIEZO cable. The speed of the vehicle was determined from the time elapsed between the pulses created by two passing axles and their respective distances. The ambient temperature was approximately 15°C (i.e., 59°F), being relatively unchanged over the 2-day period during which the experiment took place.

The methodology followed in selecting particular load values from the output of the NRCC vehicle is illustrated in Figure 4. It shows the dynamic load waveform of the first trailer axle of the NRCC vehicle, the output of the axle detector, and the selected load values corresponding to the location of the WIM scale and the PIEZO cables. It should be noted that, because of the 60-cm width of the WIM scale platform, a number of load values from the vehicle had to be averaged to yield a representative value of the dynamic load.

The experiment was performed over a 3-day period in October 1987. Three independent variables were considered: the tire inflation pressure, the vehicle speed, and the suspension type. Their respective code names and levels are listed in Table 5. It should be noted that the inflation pressure of the tires on the drive axles was not lowered to 80 psi because of

TABLE 1 PAVEMENT ROUGHNESS AT TEST SITE (INTERNATIONAL ROUGHNESS INDEX)

INTERVAL (meters)	AHEAD OF WIM (in/mi)	AFTER WIM (in/mi)
50	70	151
100	96	136
150	87	94
200	79	83
250	78	86
300	149	77
350	173	113
400	144	231
450	99	116
500	126	79
AVERAGE	110	117

Notes: 1. Roughness was measured with a Surface Dynamics Profilometer (10) and IRI was calculated according to (11).

2. 63.36 in/mi IRI = 1 m/km IRI

TABLE 2 DATA RECORDED ON NRCC VEHICLE

RECORDED CHANNEL	FUNCTION	STATUS
1	Voice	OK
2	First Tractor Axle Right Strain Gauge	
3	First Tractor Axle Left Strain Gauge	
4	Second Drive Axle Right Strain Gauge	OK
5	Second Drive Axle Left Strain Gauge	OK
6	Lift Axle Right Strain Gauge	
7	Lift Axle Left Strain Gauge	
8	First Trailer Axle Right Strain Gauge	
9	First Trailer Axle Left Strain Gauge	
10	Second Trailer Axle Right Strain Gauge	OK
11	Second Trailer Axle Left Strain Gauge	
12	Fifth Wheel	
14	Laser-Based Axle Detector	OK

OK indicates a good signal throughout testing

TABLE 3 STATIC AXLE LOADS IN kN (1,000 LB) OF NRCC VEHICLE

	LIFT AXLE	
AXLE	UP	DOWN
Steering	57.5 (12.9)	54.6 (12.3)
First Tractor	104.2 (23.4)	90.1 (20.3)
Second Tractor	103.2 (23.2)	89.7 (20.2)
Lift	-	77.8 (17.5)
First Trailer	100.0 (22.5)	73.1 (16.4)
Second Trailer	102.9 (23.1)	76.3 (17.2)
GROSS VEHICLE WEIGHT	467.8 (105.2)	461.6 (103.8)

TABLE 4 RUN NUMBER DESIGNATION AND LEVEL OF VARIABLES TESTED

RUN	TIRE PRESSURE kPa (psi)	SPEED km/h (mph)	LIFT AXLE
2	689.5 (100)	40 (25)	Down
4	689.5 (100)	40 (25)	Down
5	689.5 (100)	40 (25)	Down
6	689.5 (100)	40 (25)	Up
9	689.5 (100)	60 (37.4)	Down
10	689.5 (100)	60 (37.4)	Up
12	689.5 (100)	80 (50.7)	Down
13	689.5 (100)	40 (25)	Up
14	689.5 (100)	40 (25)	Down
15	689.5 (100)	60 (37.4)	Down
16	689.5 (100)	60 (37.4)	Down
18	689.5 (100)	60 (37.4)	Up
20	689.5 (100)	60 (37.4)	Up
39	551.6 (80)	40 (25)	Up
40	551.6 (80)	40 (25)	Down
41	551.6 (80)	60 (37.4)	Down
42	551.6 (80)	60 (37.4)	Up
43	551.6 (80)	80 (50.7)	Up
44	551.6 (80)	80 (50.7)	Down
45	551.6 (80)	40 (25)	Down
46	551.6 (80)	40 (25)	Up

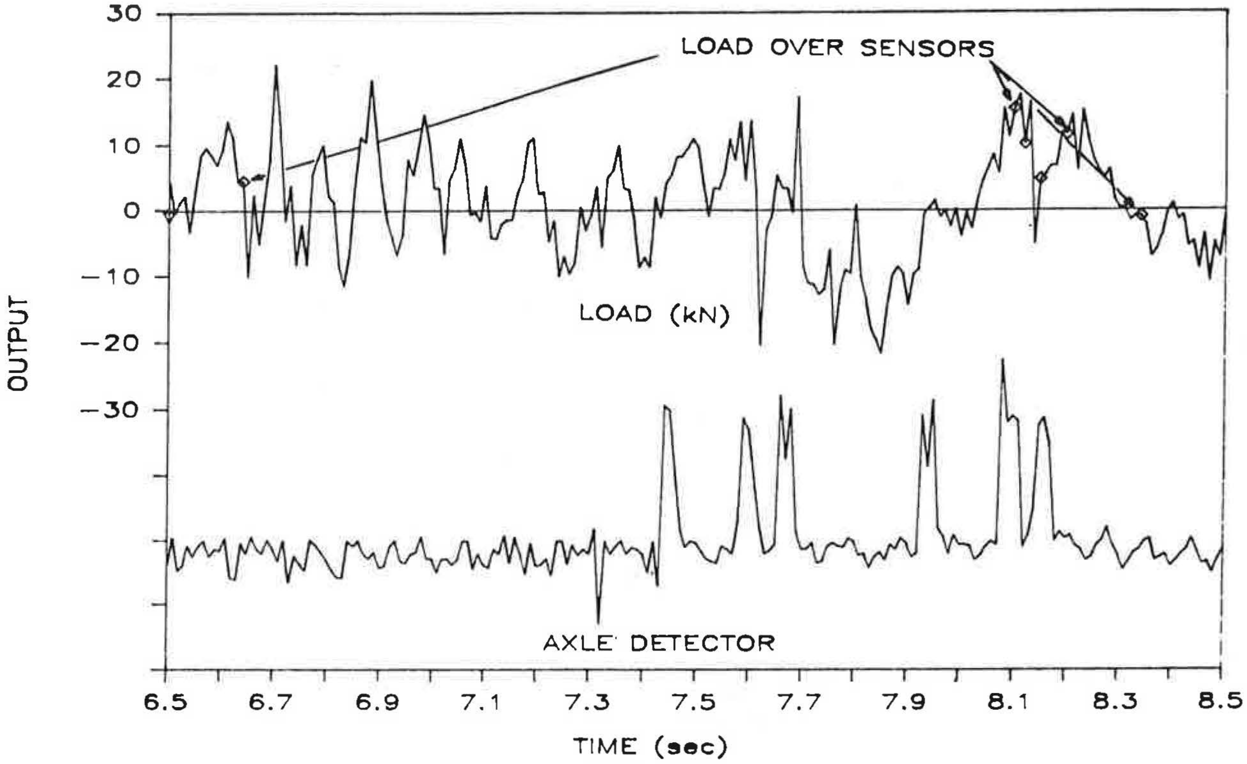

FIGURE 4 **Dynamic load values corresponding to sensor locations.**

TABLE 5 CODE NAMES AND LEVELS OF VARIABLES TESTED

VARIABLE	CODE	LEVELS
Tire Inflation Pressure	P	689.5, 551.6 kPa, (100, 80 psi)
Vehicle Speed	V	40, 60, 80 km/h, (25,37.4 50.7 mph)
Suspension Type	SU	air, rubber
Sensor	SE	WIM, PIEZO 1, 2... 5

safety considerations (i.e., the tires would rub against each other). Three replicate runs were intended for each combination of the independent variables. Hardware problems, however, compromised the quality of a number of runs, which were not considered for analysis. The vehicle runs analyzed and the variables involved are listed in Table 4.

RESULTS

Data processing revealed that only certain channels on the NRCC vehicle functioned properly during testing. These are indicated by an "OK" status on Table 2. It can be seen that only three strain gauge channels functioned properly, namely, those on the left-hand side and right-hand side of the second drive axle and on the right-hand side of the second trailer axle. To obtain the dynamic axle load of the second trailer axle, the load obtained from the right-hand side strain gauge had to be multiplied by a factor of 2. There is no doubt that this compromises the accuracy of the dynamic load data of the second trailer axle, as discussed earlier. Thus, the evaluation of the accuracy of the WIM scale and the PIEZO cables was based on the dynamic load measurements of the second tractor axle and the second trailer axle.

The results of data processing are presented in Table 6 in the form of the percentage error of the sensor measurement with respect to the dynamic load value obtained by the NRCC vehicle, whereby PA1 designates the first PIEZO, PA2 designates the second PIEZO, and so on.

STATISTICAL ANALYSIS

The objectives of the study were addressed by statistically analyzing the calculated measurement errors. To avoid differentiating between positive and negative errors, the absolute value of the measurement errors shown in Table 6 was analyzed. The microcomputer package SYSTAT was used for the statistical analysis (*12*). The following sections deal with the sensitivity of the individual sensors to the variables tested and paired comparisons of the accuracy of each PIEZO cable to the WIM scale.

Accuracy of Individual Sensors

The first part of the study deals with the accuracy of individual weigh sensors and the variables that affect it. Table 7 shows a summary of the analysis of variance performed on the accuracy of individual sensors; the code names of the variables are listed in Table 5. It can be seen that the suspension type is a statistically significant variable (i.e., at a 90 percent confidence level) for two of the six weigh sensors. There is no reason, however, for the sensitivity of sensor accuracy with respect to the axle of the vehicle used. The observed difference is attributed to the fact that the dynamic axle loads calculated for the second trailer axle of the vehicle differ considerably from the "true" load value. The unexpectedly high errors calculated for the second trailer axle (Table 6) suggest that this is correct.

It can also be seen that two of the five PIEZO cables, namely, cables 1 and 4, are sensitive to tire inflation pressure. On the other hand, none of the weigh sensors seems to be sensitive to vehicle speed.

Comparison of Each PIEZO to the WIM

The second part of the study deals with paired comparisons of the accuracy of each PIEZO cable to the accuracy of the WIM scale. Table 8 summarizes the results of the analysis of variance of these paired comparisons. As expected, the NRCC vehicle axle used as the reference for calculating accuracy was found to be a statistically significant variable. It was decided, as a result, to consider only the data obtained with reference to the second tractor axle for the accuracy comparison. A

TABLE 6 ACCURACY OF INDIVIDUAL SENSORS (PERCENT IS WITH RESPECT TO LOAD OBTAINED BY THE NRCC VEHICLE)

	AIR SUSPENSION						RUBBER SUSPENSION					
	WIM	PA1	PA2	PA3	PA4	PA5	WIM	PA1	PA2	PA3	PA4	PA5
RUN	%	%	%	%	%	%	%	%	%	%	%	%
2	5.3	-1.9	-15.0	5.9	-11.2	-41.8	8.3	-3.6	-17.2	12.0	15.8	-4.7
4	3.0	8.3	-11.5	-8.7	8.8	4.2	7.7	-2.1	-10.5	8.2	13.1	6.8
5	11.8	-3.4	-15.5	2.1	-2.3	-8.3	7.5	-1.2	-16.9	12.5	8.3	-4.8
6	10.3	-15.2	-27.9	-6.6	-13.6	-11.5	8.1	-13.9	-14.9	4.7	-23.4	-13.8
9	7.8	-1.1	-23.9	1.0	0.8	2.7	24.0	1.0	-12.0	25.1	18.6	7.9
10	-0.5	-0.7	-23.7	-10.6	-14.4	-11.4	13.7	1.1	-22.2	-2.6	-15.1	-17.5
12	1.2	-4.5	-9.6	-5.6	-8.4	11.2	-36.3	-8.4	-17.8	-0.9	21.2	54.0
13	8.2	-17.6	-23.9	3.7	-6.3	-4.7	7.8	-14.2	-16.8	10.6	-4.1	1.1
14	10.3	-3.9	-22.4	8.2	7.4	10.9	8.8	-4.3	-7.3	8.0	31.7	19.9
15	4.9	-5.6	-21.5	8.8	-2.9	7.3	20.1	-1.4	-18.6	7.1	34.0	14.7
16	-2.4	-0.2	-14.8	-7.9	9.2	15.9	-1.8	10.0	-10.1	9.3	15.4	11.1
18	-3.5	-4.1	-6.9	-10.3	-9.8	-1.2	13.4	-6.5	-12.7	-3.5	-2.8	-10.6
20	5.6	-15.9	-7.9	-11.8	-5.9	13.5	14.6	-9.2	-8.7	-10.1	-0.3	-3.5
39	11.7	-8.4	-5.5	-5.3	7.3	-8.7	7.9	-26.7	-13.5	-5.0	-8.6	-21.1
40	13.1	-9.1	4.5	13.6	12.5	-5.8	15.9	-10.9	4.4	-2.0	21.6	-16.2
41	-0.4	5.9	1.0	2.7	9.8	2.4	33.0	-4.1	6.0	-1.1	8.6	4.3
42	-1.8	-4.2	-2.4	-10.3	2.7	-1.6	17.9	-21.6	-9.8	-13.0	-2.9	-20.4
43	-10.2	-14.0	-4.5	-13.0	-5.1	7.2	12.3	-32.5	-21.0	-27.4	18.3	7.1
44	-7.8	-3.3	-0.5	-5.9	6.7	14.0	21.5	-0.7	-1.9	-7.3	-2.4	16.9
45	7.9	1.9	0.0	-8.8	9.8	3.2	11.4	-5.8	3.9	1.4	4.3	-10.0
46	7.1	-9.7	-10.8	-7.5	-0.2	-4.6	2.2	-26.7	-12.7	-3.7	-10.8	-18.4

TABLE 7 VARIATION IN ACCURACY OF INDIVIDUAL SENSORS

SENSOR	SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F-RATIO	PROB.
WIM	P	8.807	1	8.807	0.186	0.669
	V	162.268	2	81.134	1.715	0.194
	SU	398.699	1	398.699	8.426	0.006 *
	ERROR	1750.659	37	47.315		
PIEZO 1	P	435.494	1	435.494	9.064	0.005 *
	V	80.393	2	40.196	0.837	0.441
	SU	1.693	1	1.693	0.035	0.852
	ERROR	1777.731	37	48.047		
PIEZO 2	P	106.780	1	106.780	1.915	0.175
	V	37.002	2	18.501	0.332	0.720
	SU	33.360	1	33.360	0.598	0.444
	ERROR	2063.171	37	55.761		
PIEZO 3	P	10.386	1	10.386	0.325	0.572
	V	53.180	2	26.590	0.833	0.443
	SU	15.379	1	15.379	0.482	0.492
	ERROR	1180.628	37	31.909		
PIEZO 4	P	198.388	1	198.388	3.820	0.058 *
	V	38.000	2	19.000	0.366	0.696
	SU	569.985	1	569.985	10.976	0.002 *
	ERROR	1921.421	37	51.930		
PIEZO 5	P	1.240	1	1.240	0.013	0.911
	V	374.077	2	187.039	1.924	0.160
	SU	168.451	1	168.451	1.733	0.196
	ERROR	3596.216	37	97.195		

P=tire pressure, V=speed, SU=suspension type

* = Significant at 90% confidence level

summary of the *T*-tests performed is given in Table 9. The average accuracy of the WIM scale is in the order of 6 percent, while the accuracy of the PIEZO cables varies from 6 percent up to 12 percent. One of the PIEZO cables was found to have an accuracy comparable to the WIM platform, while the other four were shown to be less accurate than the WIM platform. Considering the variance in accuracy, however, only one of the PIEZO cables was shown to be significantly less accurate than the WIM platform (i.e., PIEZO cable 2).

CONCLUSIONS

Whereas two of the five PIEZO sensors tested were found to be sensitive with respect to the tire inflation pressure, neither the WIM scale nor the PIEZO cables were found sensitive to vehicle speed.

The average accuracy of the WIM scale was found equal to 6 percent, while the average accuracies of the PIEZO cables ranged from 6 to 12 percent. One of the PIEZO cables was found comparable in accuracy to the WIM scale, while the other four were inferior. Considering the variation in the calculated mean accuracy of the sensors, however, the accuracy of only one PIEZO cable (i.e., PIEZO 2) was found significantly inferior to the accuracy of the WIM scale at a 90 percent confidence level. Future study of the accuracy of PIEZO cables should include more extensive experimentation involving a wider range of operating conditions and a larger number of passes of the instrumented vehicle. Experimentation should consider PIEZO sensors of various manufacturers as well as alternative installation methods to determine the installation that yields the higher accuracy. Finally, it is recommended that the accuracy of dynamic axle load measurements on board similar instrumented vehicles be increased by accounting for the inertial component of the load generated by the bouncing mass of the rims and tires. This can easily be done by recording the acceleration of the axles and applying Newton's second law.

TABLE 8 COMPARISON OF EACH PIEZO CABLE WITH WIM SCALE

SENSOR	SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F-RATIO	PROB.
PIEZO 1	P	284.080	1	284.080	5.636	0.020 *
	V	105.141	2	52.571	1.043	0.357
	SU	174.217	1	174.217	3.456	0.067 *
	SE	84.900	1	84.900	1.684	0.198
	ERROR	3931.686	78	50.406		
PIEZO 2	P	27.128	1	27.128	0.481	0.490
	V	23.475	2	11.737	0.208	0.813
	SU	331.359	1	331.359	5.873	0.018 *
	SE	81.363	1	81.363	1.442	0.233
	ERROR	4400.623	78	56.418		
PIEZO 3	P	0.033	1	0.033	0.001	0.978
	V	198.632	2	99.316	2.410	0.097 *
	SU	285.345	1	285.345	6.923	0.010 *
	SE	107.578	1	107.578	2.610	0.110
	ERROR	3214.791	78	41.215		
PIEZO 4	P	61.799	1	61.799	1.220	0.273
	V	96.354	2	48.177	0.951	0.391
	SU	961.052	1	961.052	18.979	0.000 *
	SE	0.710	1	0.710	0.014	0.906
	ERROR	3949.660	78	50.637		
PIEZO 5	P	1.719	1	1.719	0.024	0.876
	V	454.708	2	227.354	3.234	0.045 *
	SU	542.731	1	542.731	7.720	0.007 *
	SE	27.401	1	27.401	0.390	0.534
	ERROR	5483.707	78	70.304		

P=tire pressure, V=speed, SU=suspension type, SE=sensor

* = Significant at 90% confidence level

TABLE 9 COMPARISON OF MEAN ACCURACIES BETWEEN EACH PIEZO CABLE AND WIM SCALE

SENSOR	MEAN ACCURACY %	S.D.	COMPARISON	T-VALUE	PROBABILITY
WIM	6.405	3.973			
PIEZO 1	6.602	5.2247	PIEZO 1-WIM	0.137	0.892
PIEZO 2	12.051	8.890	PIEZO 2-WIM	2.657	0.011 *
PIEZO 3	7.527	3.454	PIEZO 3-WIM	0.976	0.335
PIEZO 4	7.385	4.011	PIEZO 4-WIM	0.795	0.431
PIEZO 5	9.143	8.654	PIEZO 5-WIM	1.317	0.195

* = Significant at 90% confidence level

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