Development of a Weigh-In-Motion Network in South Africa

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There is a system of comprehensive traffic observation (CTO) in South Africa that already provides a range of traffic flow statistics. The range includes rough estimates of road loads, in terms of the number of axles, axle masses, and the equivalent 80-kN axles (E80), obtained from samples. Recent developments such as the implementation of toll roads and the introduction of a compaign against overloaded trucks have created a need for more accurate data on road loads obtained by continuous weighing of trucks in motion. A truck-monitoring scale, which is a CTO station with added sensors such as bending plates, capacitive mats, or piezoelectric strips, was conceptualized. An experimental site with all the above-mentioned types of sensors was built, and their performance and accuracy were studied during a 5-month period. It was concluded that, given proper calibration, all sensors are sufficiently accurate for the purpose required, which is to supply pavement engineers with measured road loads, to assist with revenue audits in the vicinity of toll plazas, and to inform the law enforcement authorities of the degree of overloading on a given road. The precision of the scales was evaluated in terms of 95 percent confidence limits for the errors of individual axle mass measurements. The precision ranged from ±18 percent for the Prozess-Automatisierung Technik plate (which is the most expensive sensor), to ±28 percent for the hard-top capacitive mat and ±38 percent for the piezoelectric strip (the least expensive one). Other statistics were comparable for these three scales. Although the evaluation clearly showed the importance of calibration for the accuracy of this type of truck scale, the calibration procedures have not yet been perfected and require further work. It has been proposed that three sites be used for the improvement of the calibration and the assessment of the long-term performance of the different scales.

The current weighing-in-motion of trucks in South Africa has developed as a continuation of two major previous efforts, namely, the local research in and manufacturing of capacitive mats, which go back some 25 years, and the more recent advent of so-called comprehensive traffic observation (CTO). CTO is a system for the acquisition, by electronic means, of reliable and extensive traffic information.

The system has three main parts:

- Network of stations,
- Observation equipment, and
- Data bank that processes data and disseminates information.

At present, after about 5 years of expansion, the network has about 100 permanent and 200 secondary stations. At permanent stations traffic is monitored continuously, 24 hr a day every day, to obtain complete annual information. At secondary stations traffic is observed on a sampling basis, usually for 7 consecutive days during a nonholiday period; the annual information is estimated from the sample by using information from an appropriate permanent station.

The equipment consists of a locally developed and manufactured Traffic Engineering Logger (TEL) (*1*) solar power supply, telephone modems, connections, pairs of inductive loops buried under the road surface in each lane, and an appropriate housing at the roadside.

When a vehicle passes over loops (shown schematically in Figure 1), five principal bits of data are recorded for that vehicle and stored in the TEL's memory:

- Time of arrival,
- Speed,
- Length of vehicle,
- Chassis height, and
- Lane number.

However, in most practical applications, the data are partly condensed and stored as hourly totals. The retrieval of data from TEL's memory (which is usually 393 kb) is done by means of a data extractor using tape cassettes, a lap-top computer, or by telephone and routed to a receiving computer by means of modems. The last is the usual practice at permanent stations.

From the data thus received and some other sources, for example, separate vehicle weighings, extensive information on traffic can be derived, as shown by an example in Table 1.

The information obtained is regularly compiled into CTO bulletins, maps, and yearbooks (*2*) and is meant to fulfil the needs of practitioners in road planning and design, pavement maintenance, planning and design of toll facilities, traffic management, and law enforcement. It is to facilitate assessment of road priorities, allocation of funds and budgeting, public relations and education, forecasting, research, and special investigations.

The five bits of data mentioned above, however, contain no information on number of axles or axle loads; the inductive loops do not produce such data. In the original CTO system the equivalent 80-kN axles (E80) imposed on a road are estimated from the number of trucks observed and the average value of E80 per truck, which is derived by speculation or estimated from short-term axle mass surveys. These surveys are done on a sampling basis by means of locally manufactured capacitive mats. Averages from these surveys were used to produce the estimates of road loads shown in Section 6 of Table 1.

Since 1984 when the CTO system started, two significant events have occurred on the road scene and have caused a shift in the CTO philosophy: the implementation of toll roads

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and the introduction of a so-called vehicle control network (VCN) designed to combat overloading of trucks and their noncompliance with roadworthiness regulations.

The first impetus came from the toll roads; because toll tariffs are based on axle counts and the authorities wish to audit toll revenues by means of a dedicated permanent CTO station in the vicinity of each toll plaza, axle counting had to be incorporated into the CTO. Since 1987, piezoelectric strips have been used as axle-counting sensors; at stations in the vicinity of toll plazas and on parallel routes a strip is placed between the two loops in each lane. The original five-bit set of data was increased to a six-bit one and the data processing was modified accordingly to yield a better vehicle classification and an accurate axle count.

The success of this extension and the reliability with which it performed provided a platform from which an important step forward could be attempted, namely, the introduction of a low-cost scale for weighing trucks in motion, on a permanent basis, for purposes of pavement engineering, toll-revenue auditing, and screening of overloaded trucks. The VCN project and the inaccuracy of the road load estimates provided the other impetus—CTO had to be extended by axle weighing.

Three major fields of application have been envisaged as a result of such an extension. First, the scales will be used at permanent stations by all the road authorities already engaged in the CTO program (the departments of transport in South Africa and South West Africa/Namibia, and the roads departments in the provinces of Transvaal, Natal, and the Orange Free State), and possibly by a new user—the Cape Roads Department. Their reasons for use will be a substantially improved vehicle classification, accurate measurement of road loads in terms of average E80, and identification of routes with an overloading problem to arrange for priority law enforcement.

Second, the operators of both the state and private toll roads are likely to use the scales for revenue audit, road maintenance, and monitoring the residual value of pavement and extent of overloading. It is possible that the availability of such scales would lead to the introduction of a more equitable truck toll tariff based on degree of loading (e.g., not loaded, legally loaded, overloaded).

Finally, when the planned VCN project is implemented, the truck monitoring scales working in the CTO framework will provide feedback and evidence on the degree to which

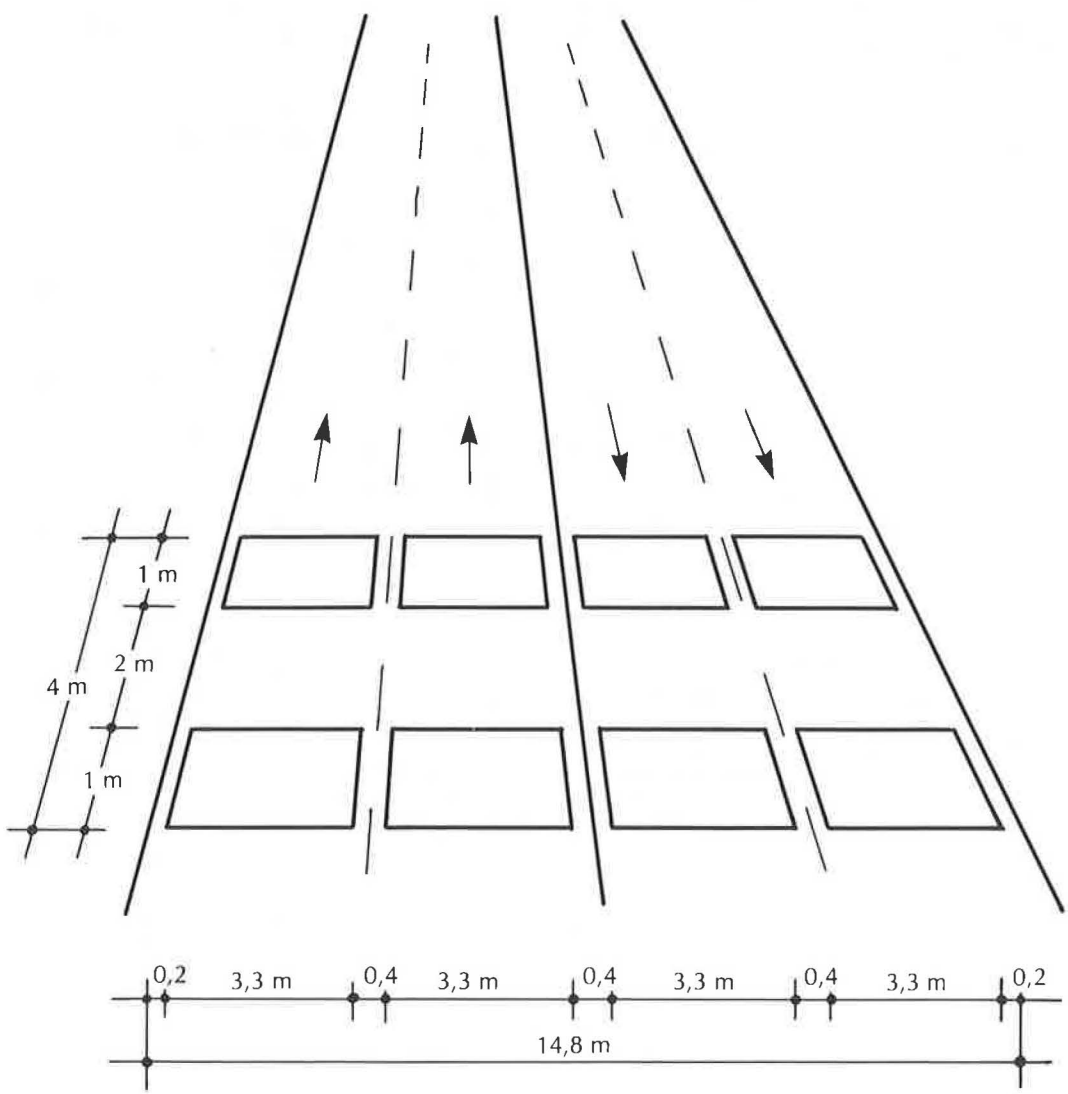

FIGURE 1 Typical layout of loops.

TABLE 1 EXAMPLE OF HIGHLIGHTS OF CTO ON MAJOR ROADS IN 1988

1 GENERAL	1.1	Route number	N 001	N 001	N 002	N 001	N 002
	1.2	Road and section number	N 001-23	N 001-24	N 002-08	N 001-14	N 002-31
	1.3	Station name	SETTLERS	KRANSKOP	TSITSIKAMMA	EDENBURG	MKUZE
	1.4	Station number	041	301	034	117	114
	1.5	Station operation regarded as :	PERMANENT	PERMANENT	PERMANENT	SECONDARY	SECONDARY
	1.6	Data collection standard	RECOMMENDED	RECOMMENDED	RECOMMENDED	RECOMMENDED	RECOMMENDED
	1.7	Date of latest record	88-12-31	88-12-31	89-01-02	88-11-14	88-09-07
	1.8	Length of record, hours	6614	7309	8220	1408	312
	1.9	Traffic similar to that :	-----	-----	-----	PORT ALFRED	RUSTENBURG
2 COUNTS	2.1	Total number of vehicles observed	1958757	1790396	481992	163672	14437
	2.2	Average daily traffic (AADT) veh/day	7249	5914	1311	2444	1126
	2.3	Average truck traffic (AADTT) truck/day	561	478	154	510	240
	2.4	Percentage of trucks	7.7	8.1	11.7	20.9	21.3
	2.5	Truck split, % short:medium:long	43:39:18	45:38:17	32.39.29	7:53:40	42:29:29
	2.6	Night traffic, percentage of vehicles	11.7	13.2	8.9	15.7	8.6
3 SPEEDS	3.1	Speed limit, km/h	120	120	120	120	100
	3.2	Average speed, km/h	110.4	92.8	80.6	108.6	75.4
	3.3	Average speed - light vehicles, km/h	113.2	95.5	84.0	114.6	87.2
	3.4	Average speed - trucks, km/h	85.6	70.3	60.7	93.8	51.9
	3.5	Average night speed, km/h	98.7	80.0	72.8	104.2	63.1
	3.6	85th centile speed, km/h	134.4	115.3	101.3	131.1	109.0
	3.7	Percentage of vehicles exceeding speed limit	41.2	8.9	2.2	36.0	29.2
4 FLOWS	4.1	Percentage of vehicles in flows over 600 vehs/h	1.2	0.9	0.0	0.0	0.0
	4.2	Highest volume recorded on the road, vehs/h	2119	1668	391	707	136
	4.3	in the northbound (eastbound) direction, vehs/h	1932	1558	203	408	93
	4.4	in the southbound (westbound) direction, vehs/h	1497	1176	278	557	64
	4.5	30th highest volume recorded on the road, vehs/h	1358	1199	316	405	89
	4.6	in the northbound (eastbound) direction, vehs/h	902	910	168	194	48
	4.7	in the southbound (westbound) direction, vehs/h	985	792	171	270	45
	4.8	Highest volume in one lane, vehs/h	1186	851	278	577	93
5 QUALITY OF SERVICE	5.1	% of vehicles travelling at speeds over 80 km/h	94.7	83.1	62.6	94.5	65.8
	5.2	% of vehicles less than 2s behind the vehicle ahead	6.3	4.6	3.9	7.5	3.4
	5.3	% of vehs incurring no extra cost due to congestion	94.7	100.0	100.0	100.0	100.0
	5.4	Cost of congestion, R/km per day	0.0	0.0	0.0	0.0	0.0
6 ROAD LOADS	6.1	Average number of axles per truck	3.7	4.0	3.1	5.5	4.3
	6.2	Average truck mass, t/truck	21.8	23.5	27.1	33.2	25.1
	6.3	E80 per truck	1.49	1.57	2.03	2.20	1.59
	6.4	Average daily E80 (ADE80) in worst lane	466	375	176	530	196
	6.5	Traffic class of road	E3	E3	E2	E3	E2
7 GROWTH RATES	7.1	Number of weeks analysed	196	86	230	--	--
	7.2	Growth rate of all traffic, % p.a.	24.2	15.3	7.0	--	--
	7.3	Growth rate of truck traffic, % p.a.	25.7	20.6	11.1	--	--
	7.4	Growth rate of E80 in worst lane, % p.a.	26.6	0.1	18.8	--	--

the VCN operation is effective with respect to the whole network of major roads. In addition, the monitoring scales will indicate on which escape routes supportive law enforcement is required.

The aim of this paper is to describe briefly the current status of electronic traffic measurements in South Africa, and to mention factors that gave the present system its shape. The paper then concentrates on the testing and comparison of three different types of weigh-in-motion sensors under full-speed conditions and examines their suitability for purposes such as supplying information for pavement engineering, toll revenue auditing, and identification of the extent of truck overloading.

DEVELOPMENT AT LYDIANA

To create a platform from which the above-mentioned applications could be launched, the Department of Transport (DOT) sponsored a development project called Permanent Monitoring Truck Scales (*3*).

Three types of axle mass sensors were locally available and were used in this project, namely,

1. Bending plates manufactured by Prozess-Automatisierung Technik (PAT);
2. Piezoelectric strips supplied by Flow Electronics (FE); and
3. Two types of capacitive mats provided by the Division of Roads and Transport Technology of the Council for Scientific and Industrial Research (CSIR). One mat was the commercially available Series 8 sensor (so-called soft-top), which is manufactured by Electromatic, and the other (Series 9 sensor, a hard-top) was a prototype sensor specifically developed for this project.

For the purpose of the project an experimental station was built at Lydiana (on N4-1, near the CSIR Campus, Pretoria, where the four-lane freeway carries over 30,000 vehicles per day) in November 1988. Four sets of axle-weighing sensors (two types of capacitive mats in one lane, one piezoelectric cable in each lane, and a PAT bending plate in one lane) were embedded in the road, flush with the road surface, about 30 m apart. Each sensor was connected to its own TEL machine so that all four sets could work simultaneously and be compared under identical traffic.

In a period of 5 months, from November 1988 to March 1989, the Lydiana site was used extensively and continuously for the development of the necessary hardware (i.e., the interfaces between the weighing sensors and TEL machines), for testing, modification and calibration, the preparation of the required firmware and software, and for the evaluation of performance and accuracy of the individual truck scales.

The evaluation of accuracy entailed establishing errors with which individual truck axles were weighed by the four truck scales under test and the determination of errors in the total gross vehicle mass and the total E80.

The accuracy was tested on three occasions:

1. On Thursday, February 23, 1989, a fixed fleet of three trucks (two-axle, three-axle, and six-scale), with axles loaded from 2.86 to 8.84 t was weighed accurately on a static platform weighbridge five times (to have an absolutely reliable reference for the evaluation of errors). Throughout the day, this fleet then passed over all four scales 39 times, at speeds varying from 30 to 70 km/hr and at different road surface temperatures.
2. On Thursday, March 16, 1989, a fleet of five vehicles (a pick-up, a two-axle light truck, a two-axle truck, a three-axle truck, and a six-axle truck, a total of 15 axles) was weighed once on the static platform weighbridge. The fleet then passed over all four scales 26 times, in a manner similar to that of the previous test.
3. On Friday, March 17, 1989, a sample of 55 trucks was selected from the traffic stream in a random manner and weighed, axle by axle, on a static axle scale at Donkerhoek, some 20 km upstream. Most of these trucks then passed over the four scales at Lydiana, where their axle loads were recorded. The axle loads determined at the Donkerhoek weighbridge were then used as a reference for the evaluation of errors.

TEST RESULTS

It was noted that the performance of the four truck scales varied from test to test, mainly because of bias caused by calibration. It has been found that the difference between measured and static axle mass becomes larger as the axle mass increases; in other words, the coefficient of variation remains constant. All variations were therefore normalized by using the following:

$$\text{Error} = \frac{\text{measured axle mass} - \text{static mass}}{\text{static mass}}$$

Other researchers (*4*) have used the concept of impact factor, which is the dynamic mass divided by the static mass, to normalize the results. The error concept is preferred, because the deviations from the static mass are not necessarily attributable only to impact, impact effects are largely taken into account when site-specific calibrations are developed. Furthermore, when total mass or equivalent standard axles is considered, error has more significance than impact factor.

The average error, or bias, was then determined by averaging all the errors. Then 95 percent confidence interval for the error of individual axle masses were calculated as the standard deviation of individual errors multiplied by 1.96. Other statistics that were calculated like those above were in total mass measured and in total equivalent standard axles (E80).

To give an indication of the potential of each scale, Table 2 was compiled, which compares the four truck scales and shows their errors during the test in which a given scale performed best, that is, least errors in the total tonnage and the total E80. For interest, the approximate costs of sensors are also given in Table 2. Figure 2 shows the data for the comparison between static and dynamic weight collected on March 17, 1989, for the four systems. The lines shown are the lines of equality. Note that no data were discarded, not even apparent outliers.

TABLE 2 COMPARISON OF TRUCK SCALES

1	Manufacturer	PAT	DRTT	ELECTROMATIC	FLOW ELECTRONICS
2	Type of sensor	DAW200	CAWS-9	CAWS-8	P-1/SI
3	Shape and principle used	Steel plate with strain gauges	Hard-top capacitive mat	Soft-top capacitive mat	U-channel strip with piezoelectric cable
4	Cost per lane (incl. installation)	R45 000	R14 000	R14 000	R5 000
5	Best results obtained in the test on	23/2/89	17/3/89	23/2/89	23/2/89
6	Number of anxles analysed	418	114	374	308
7	Average % error of individual axle masses	+ 0,8 %	- 1,5 %	+ 1,2 %	- 6,5 %
8	95 % confidence limits of the above error	± 18 %	± 28 %	± 30 %	± 38 %
9	Error in the total gross vehicle mass	+ 1,4 %	- 3,3 %	+ 1,4 %	- 8 %
10	Error in the total E80 equivalents	+ 15 %	- 15 %	+ 18 %	- 26 %

COMMENTS

The average percentage error with which the individual axles were weighed (see the seventh line in Table 2) reflects directly the quality of calibration, whereas the next line—the 95 percent confidence limits—indicates the precision of a scale. It is evident that calibration errors are carried over into both the error in the total mass (Line 9) and the total E80 (Line 10). To achieve reasonable accuracy it is essential to keep the calibration error as small as possible, whereas the lack of precision of a scale is of secondary importance. The reason lies in statistics—when totals of hundreds of axles are calculated, there are hundreds of opportunities for the individual errors to cancel each other. Because of this, even a low-precision scale can produce relatively accurate totals, on condition that the calibration error is small (see the example in the last column of Table 2). The least precise scale—that using piezoelectric cables—produced readings of individual axle weights deviating from the truth by up to 38 percent. (Strickly speaking, 95 percent of the readings were likely to deviate by up to 38 percent and the remaining 5 percent of the readings by even more.) Yet the total mass of 308 axles was burdened by a small error of minus 8 percent only, and the total E80s by an acceptable error of minus 26 percent. It should be pointed out that the main factor responsible for these errors was the 6.5 percent calibration error rather than the low-precision nature of the scale.

During the 5-month period the sensors in the road performed well and proved to be sufficiently robust for the job required. By sheer coincidence, on November 30, 1988, a truck with a flat tire went over all four sensors and thus provided an unexpected opportunity to test the strength of the sensors. The PAT plate and the piezoelectric sensors emerged unscathed. Both the hard-top and soft-top sensors were dented by a shallow groove, which, however, did not impair their performance. Nevertheless, to be on the safe side, both mats were replaced. Shortly after the installation of the piezoelectric cables, one 0.5-m-long polyurethane insert disappeared and had to be replaced. Since then the performance of the piezoelectric cables in all four lanes has been trouble-free.

Other problems experienced were the occasional breakdowns of equipment, moisture ingress into cabling, and some crosstalk in inductive loops, particularly after heavy rains.

The development of the TEL firmware, which was done in stages, added a variable string—the weight of each axle—to the previously mentioned six-piece set of data. The latest version is the outcome of about seven modifications and includes telecommunications facilities for remote monitoring of individual vehicle data including weights and extraction of records by telephone. It also features so-called data compression for faster and more economic transfer of data from TEL to the receiving computer. The firmware is in fact a set of program modules that allows the operator to choose one of three levels of information aggregation and one of the three axle-monitoring options (no recording of axle data, counting of axles only, and both counting and weighing of axles). The set was tested extensively and proved to be capable of handling traffic of over 30,000 vehicles per day with recording data on each individual vehicle in the axle-weighing mode.

The software, that is, the computer programs converting TEL data into information, was modified to handle the new output format. As a consequence, the estimates, obtained by measurement, of three interesting characteristics could be added to the information on road loads, namely,

- Percentage of axles exceeding the 8.2-t mass limit,
- Percentage of trucks exceeding the maximum permissible gross vehicle mass, and
- The amount of illegal E80 imposed on the road by overloaded trucks.

One aspect of the work has not yet been completed satisfactorily, namely, the calibration. This is evident from the variation in the calibration error (i.e., in the average percentage

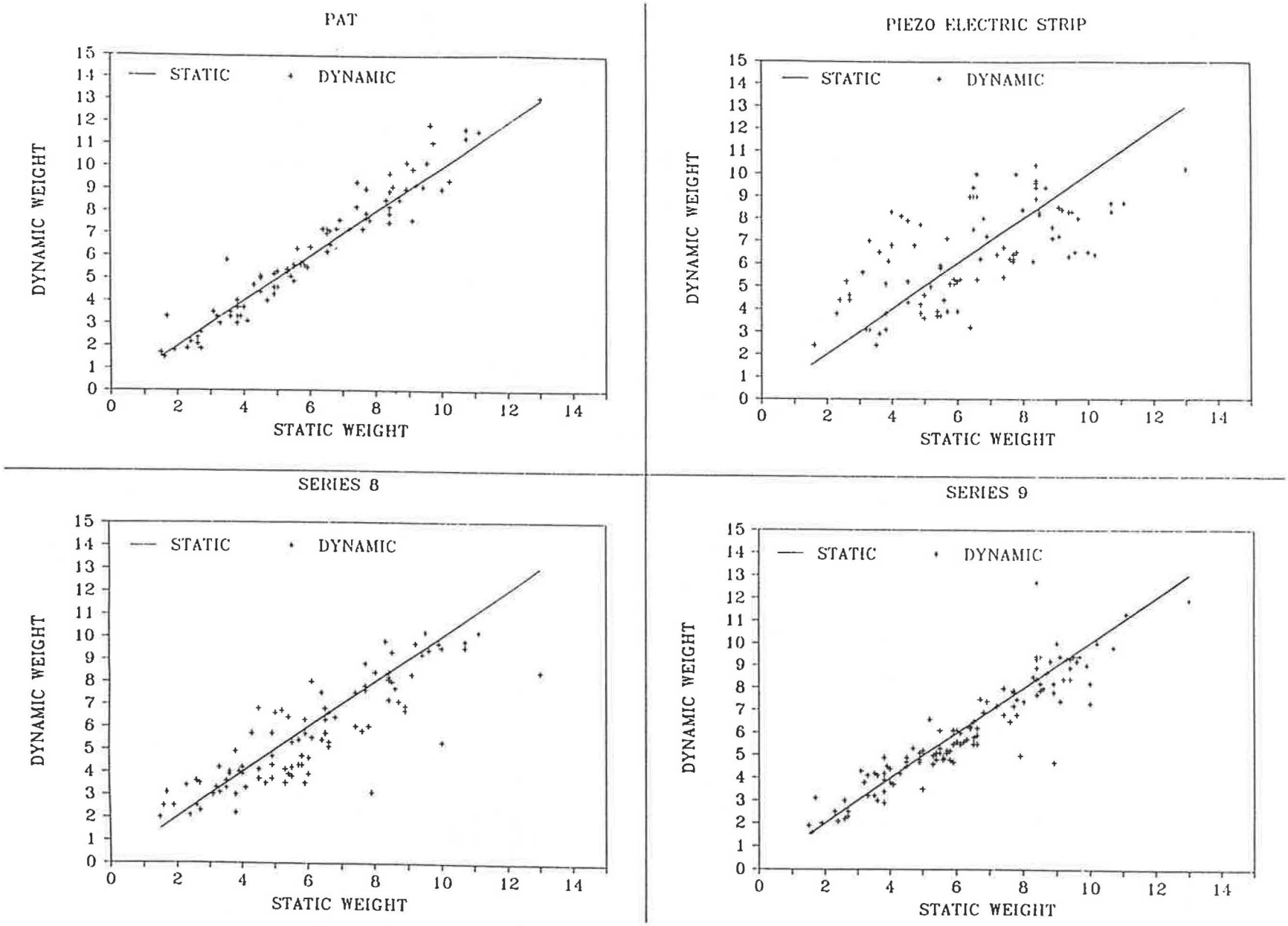

FIGURE 2 Comparison of static and dynamic axle measurement on March 17, 1989.

error of individual axle masses) from scale to scale and from test to test (see Table 3).

Calibration error is influenced by two main factors, namely,

1. The strength of signals received from the sensor (which can be increased or decreased by electronic means) and
2. The conversion of signals into axle weights by means of a mathematical formula, empirical curve, or a computer look-up table.

In practice, calibration is done by observing sensor response to the passage of an assortment of trucks with a variety of axles of known weight, ranging from light to heavy, traveling at different speeds, on road surfaces of diverse quality and evenness, under various thermal and humidity conditions. The objective is to amplify or attenuate the signals and then subject them, together with other factors, to a conversion procedure that would yield a minimum average error of individual axle mass measurements.

Arranging for the variety of conditions described above with a view to calbration is a difficult and rather expensive task. After weeks of trial and error at the Lydiana site, a consensus was reached that

1. Using a heavy axle (preferably in excess of 12 t, i.e., a 50 percent overload) is essential for good calibration, and
2. Precalibration of sensors in a laboratory (or on a good site with a reference scale) may be necessary before the sensors are shipped to the actual site, where calibration should then be completed with the help of at least one heavily loaded truck with known axle weights.

An important finding of the study was that as long as the bias was within 10 percent, reasonable statistics for total mass and total E80s could be expected. This means that fairly straightforward techniques could be used to develop calibration curves. Although the operators may have control over the magnitude of the bias, they have little control over the variability of individual axles. This is a combined effect of the repeatability of the sensor, the evenness of the approaches to the sensors, and the varying dynamic response of the different suspension systems. The small bias obtained in this comparison between static and dynamic effects compares favorably with results of dynamic comparisons presented by Papagiannakis et al. (*4*). In their case accuracy, or bias, varied between 6 and 12 percent for a piezo cable and a bending plate system. Variability was, as expected, smaller than in this study, ranging in 95 percent confidence intervals from 7 to 17 percent. For a previous study with a Series 8 capacitive mat mounted on the surface a 95 percent confidence interval of 18 percent was found (*5*) and there was no bias. There is no apparent reason for the poorer performance in this study. This finding fortunately has consequences for the truck monitoring scale project, because the Series 9 was specifically developed for permanent installation and flush mounting, rather than the Series 8, which was developed for surface mounting. The results of Moore et al. (*6*) for the capacitive mat and piezo cable are also similar to those found in this study.

When a small fleet of well-maintained vehicles is used to validate the accuracy of dynamic weighing systems, the variability is smaller than when random vehicles from the traffic stream are used. This may be attributed to the state of road maintenance or to the vehicle suspension characteristics. This fact should be appreciated when routine data collection takes place.

CONCLUSIONS

The outcome of the project can be summarized as follows:

1. The idea of permanent truck-monitoring scales is feasible.
2. Three of the sensors tested (PAT plates, hard-top mats, and piezoelectric strips) seem to be sufficiently robust for the CTO applications.
3. All three types of sensor have the potential to produce information good enough for the purposes required, that is, to supply measured road loads, to assist with reveune auditing in the vicinity of toll plazas, and to indicate the degree of overloading on a given road. Note, however, that they were never considered to be suitable for direct law enforcement purposes.
4. The most precise (but most expensive) sensor is the PAT plate. The least precise (but the cheapest) is the piezoelectric strip.
5. If a sensor is well calibrated, its precision is of secondary importance—the error in the total mass and E80 of thousand of trucks will be relatively small anyway because of the propensity with which individual axle errors tend to cancel each other.
6. The project has yielded electronic hardware, firmware, and software that is capable of weighing truck axles in motion with a reasonable degree of accuracy. The products cover the whole spectrum, from signal processing to reporting and information dissemination structures.
7. The degree of accuracy depends, to a large extent, on the calibration. However, the art of calibrating has not yet been mastered fully—more work in this field is required to ensure reliable and consistent results at different sites and in different conditions.

TABLE 3 CALIBRATION ERRORS

TEST \ SCALE	PAT	HARD TOP	SOFT TOP	PIEZOELECTRIC
23 February 1989	+ 0,8 %	+ 12 %	+ 1,2 %	- 6,5 %
16 March 1989	+ 5,4 %	- 5,4 %	+ 27 %	+ 19 %
17 March 1989	+ 0,9 %	- 1,5 %	- 3,2 %	+ 8,9 %

RECOMMENDATIONS

The idea of permanent truck-monitoring scales is feasible, and with the developments demonstrated it was recommended that other road authorities give serious consideration to installing a CTO-type system with vehicle-weighing capabilities.

With the experience gained during the work on the project, two particular recommendations were made to the client:

- That the experimental facilities be maintained at Lydiana for further development and to perfect the calibration procedure and
- That the piezoelectric installation at Lydiana be maintained as the first permanent truck scale and that one additional site be equipped with capacitive mats and one with a piezoelectric sensor. These sites would be used to assess the durability of the sensors, their maintenance requirements and cost, and other operation-related aspects.

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