

Weigh-in-motion: years of South African experience

M Slavik

Weigh-in-motion (WIM) applications in South Africa – a country with 50 years of weigh-in-motion history – include routine traffic load monitoring for purposes of pavement design and maintenance, selection of heavy vehicles for accurate weighing and possible prosecution, guidance of traffic police to roads with a serious overloading problem, periodic auditing of operation of static weighbridges, and the estimation of pavement damage caused to roads by overloaded heavy vehicles.

WIM is a scale that measures dynamic forces applied to road surface by passing wheels. Yet, most users expect WIM to imitate static weights of vehicle axles. This expectation causes a number of problems related to accuracy, calibration and interpretation of measurements. Because of economic reasons half-lane high-speed WIMs are frequently used in this country. Pavement deterioration, poor installation and site maintenance dominate the list of reasons when these do not perform well.

Several measures have been devised and implemented to alleviate the difficulties regarding WIM accuracy. Extensive WIM data checks and validations are undertaken monthly. A software correction method has been proposed to suppress systematic and random WIM errors. Continuous monitoring of the so-called truck-tractor tonnage trends has been implemented and used as a diagnostic tool. Recently, the responsibility for the installation and maintenance of WIM sites has often been transferred from the user to specialised and highly competent WIM service providers – their customers pay for good information rather than WIM equipment, which they do not know how to operate and service.

Notwithstanding all the above, WIM users should accept that WIM measurements have limited accuracy and may occasionally be burdened by considerable errors. Although being ideal to establish the order of magnitude and facilitate comparison of loads applied, the WIM measurements are not suitable for litigation purposes.

In the future, changes in the Road Traffic Act allowing dynamic vehicle weighing for prosecution purposes could initiate further WIM proliferation and development. Also, WIM would play a prominent role should comprehensive road pricing become a reality.

BACKGROUND

Weigh-in-motion (WIM) is a technique for the measuring of axle loads without stopping vehicles. The measurement is fast and unobtrusive. From the loads of individual axles one can derive the mass of axle groups and the gross vehicle mass, plot the axle-load distribution, and calculate equivalent standard axle loads (ESAL). Pavement designers use the axle-load distributions and ESAL as input into design models. Traffic police enforcing anti-overloading laws are interested in loading of individual vehicles; they also wish to know where and when these vehicles travel, and how significantly they are overloaded. Policy-makers and legislators seek overall evidence to assist them in informed decision making.

For the above reasons, many WIM installations operate daily and on a routine basis in dozens of countries all over the world, including South Africa.

The history of South African WIM started in the mid-1950s when the Council

for Scientific and Industrial Research (CSIR, its National Institute for Road Research in particular) decided to develop an 'affordable weighbridge to measure traffic'. The original design used piezo-electric sensors. However, these did not perform satisfactorily and were later replaced by capacitive mats. After an initial measure of success the capacitive mats were further developed and went to commercial production in the mid-1970s. Since then many improvements have been made to the South African capacitive mats. This is the technology that has been, and still is, used at many WIM stations in this country and internationally.

During the 1980s the use of WIM was sporadic, mostly for the purpose of pavement design and maintenance, with measurements of dubious accuracy. By the end of the 1980s the majority of road authorities in this country fully realised and appreciated the extent of damage caused to roads by overloaded heavy vehicles. To control the situation several new weighbridges

TECHNICAL PAPER

JOURNAL OF THE SOUTH AFRICAN INSTITUTION OF CIVIL ENGINEERING

Vol 49 No 1, 2007, Pages 11–16, Paper 617



MARTIN SLAVIK is a specialist engineer and associate of BKS. He graduated from the Czech Military University in 1958, and received a master's degree in transportation from the University of California at Berkeley, and a DSc degree from the University of Pretoria.

He has been involved with electronic traffic observations and weigh-in-motion technology for over 35 years; first at the National Institute for Transport and Road Research, CSIR, then, since 1983, at BKS. Apart from these, his recent activities include control of truck overloading and development of computer simulation techniques for the design of rigid and flexible pavements.

Contact details:

BKS (Pty) Ltd
PO Box 3173
Pretoria, 0001
T 012-421-3500
F 012-421-3501
martins@bks.co.za

Keywords: weigh-in-motion, accuracy, calibration, evaluation, validation



Figure 1 Typical half-lane high-speed WIM installed on a freeway. Another sensor and a set of inductive loops are across the median, for the other direction of travel

were planned and many existing ones refurbished. In the wake of this effort an additional application of the WIM emerged: the so-called screening of heavy vehicles upstream of a weighbridge, to segregate the minority of overloaded vehicles from the legally loaded vehicles. This protected the weighbridge from over-use and reduced inconvenience to law-abiding truckers. The screening application provided an impetus for further development and proliferation of WIM technology. Imported bending plates using strain-gauge technology were tested and their accuracy compared with that of the local capacitive mats and the locally manufactured piezo-electric sensors.

Another and even stronger impetus came in the second half of the 1980s when toll roads reappeared on the South African transportation scene. In the case of concession roads, contracts stipulated that the road authorities would control overloading, and if not, the concessionaire could claim for damages. To obtain evidence in this respect a number of WIM stations have jointly been constructed and continuously operated by the road authorities and private sector. The main purpose of these stations is to collect data on the effectiveness of law enforcement, and inform on extra ESAL due to overloading.

WIMs also operate as screening scales on roads with weighbridges. Although these are linked with the weighbridge information system, they operate independently, so that their data can be used for monitoring, checking, and auditing the weighbridge performance. The WIM data also provides guidance to mobile law enforcement by indicating the incidence, extent and severity of overloading.

In 1999 the Department of Transport introduced a standard for WIM data (Schildhauer 1999) that has subsequently been implemented throughout the country. This important step laid the foundation for uniform nationwide WIM data collection, validation, interpretation, publishing and archiving.

At present, 56 permanent WIM stations are operating on various national and provincial roads in South Africa.

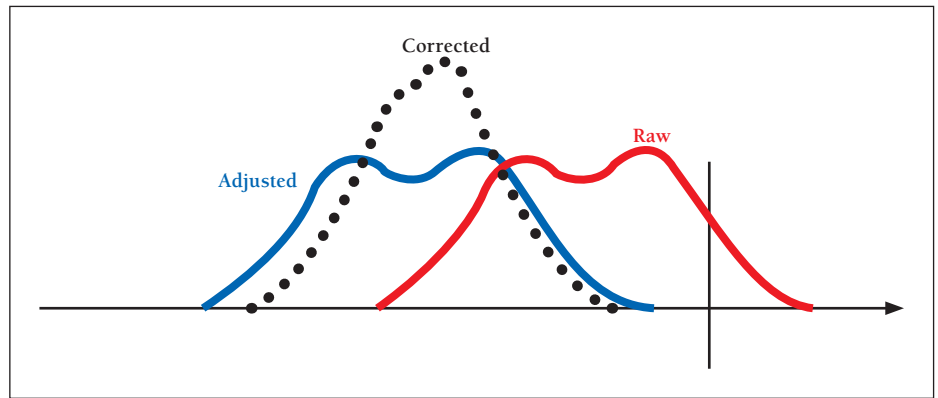


Figure 2 Raw, adjusted and corrected axle load distributions

For economic reasons, the majority of the WIMs have a single sensor in the outer lane, as shown in figure 1. The sensor is approximately a half-lane (1,8 m) wide. Each sensor receives, at vehicle travelling speed, wheels on the left-hand side of the vehicle. In most applications the sensors are placed in ordinary traffic lanes, even in the case of screening. Only a few screening WIM stations use two sensors in a dedicated heavy-vehicle lane where there is a 40 km/h speed restriction – one in each wheel path.

Although economical, the half-lane single-sensor high-speed WIM arrangement is a rich source of headaches. The most prominent of these problems, together with some solutions, are briefly discussed in the subsequent sections of this paper.

ACCURACY OF WIM DATA

The root of the accuracy problem is in the principle – WIM weighs vehicles dynamically whereas users expect static loads. The South African Road Traffic Act stipulates the maximum permissible loads of axles, axle units, vehicles and vehicle combinations in terms of masses measured statically, that is, while the vehicle is stationary. The pavement design practitioners currently calculate stresses and strains in various layers using static loads. The fact is that WIM cannot supply static loads – it is, and always has been, a dynamic scale. Historically, huge effort has gone into 'teaching' WIM to imitate static loads. In practice this is attempted through skilful adjustment of measured values by means of hardware and/or software. The adjustment relies on the comparison between the WIM loads measured during the calibration and their known static counterparts.

The WIM users have to accept that the imitation is not very accurate. For the WIM arrangement described above, a widely adopted American standard (ASTM 2002) allows differences as large as $\pm 20\%$ between dynamic and static axle-loads (using static load as reference).

The author proposed a method called Slimax (Slavik 2004) based on theory developed earlier (Slavik 1998) to alleviate this problem. Slimax distinguishes between three

versions of axle loads, namely raw, adjusted, and corrected. Raw (that is, as-measured) axle loads are burdened both by systematic (calibration) and random (inexplicable) errors. In the first step Slimax applies adjustment factors obtained during calibration to individual raw axle loads and thus transforms these loads into adjusted ones. This eliminates or suppresses the systematic error. In the next step Slimax converts adjusted axle loads into corrected ones. The conversion process is based on two conditions:

- The mean corrected axle load must equal the adjusted one
- The variance of the corrected axle loads must equal the variance of the adjusted ones minus the variance of WIM's random error

This step suppresses the random error. The corrected axle loads are then used to derive characteristics such as the percentage of overloaded vehicles and average ESAL per heavy vehicle.

The concept is apparent from the sketch of three axle-load distributions shown in figure 2. Axle loads as measured by WIM are red, adjusted axle loads blue, and the corrected distribution is black. Based on the available information the dotted black distribution approximates the distribution of true static axle loads.

The Slimax method was used on an experimental basis on several occasions. Despite its simplicity and ease of use – a user-friendly computer program does the calculations very quickly – to date it has not gained sufficient acceptance and popularity to be used on a routine basis.

OVERESTIMATION AND ESAL INFLATION

Pavement practitioners require ESAL evaluated from actual measurements of axle loads. The commonly used conversion formula is

$$ESAL = (AL / 8,2)^{4,2}$$

where AL is axle load in tons.

If WIM over-measures a 9 t axle load by the permitted 20 % then the above formula

over-estimates ESAL by 115 % – a huge error that challenges the practicality of such estimation.

Should WIM under-measure the 9 t axle load by 20 % then the ESAL would be under-estimated only by 61 %.

As is apparent from the above values the positive and negative errors have different magnitude and do not tend to cancel each other. When WIM-measured axle loads are used for the estimation of ESAL a propensity for over-estimation is always present. This is true even in the absence of WIM systematic error, that is, when WIM is calibrated correctly. The greater the WIM random error is, the more severely inflated is the estimate of ESAL.

An alleviation of this problem could come from the application of the Slimax method. However, at present the over-estimated figures of ESAL derived from raw axle loads are tolerated by road authorities and accepted by practitioners who prefer to err on the conservative side.

UNCERTAINTY ABOUT OVERLOADING

The question most frequently asked regarding traffic loading is: What is the percentage of overloaded vehicles?

Excessive loading may occur at two levels:

- Between the legal and the so-called *grace* limit
- Over the grace limit

For compassionate and practical reasons a certain amount of grace is given to offenders before they are prosecuted for overloading. Currently up to 5 % excess above the legal limit is condoned in South Africa. Experience on truck routes shows that a vast majority of truckers have mastered the art of loading and are converting the allowed grace into a commercial advantage – whenever possible they overload their trucks by up to 5 %, but not more on routes with strong law enforcement. This trend causes the general percentage of ‘over-the-grace’ overloading to decrease and the ‘within-the-grace’ overloading to increase. For this reason the percentage of ‘over-the-grace’ overloading is commonly used to quantify the extent of overloading, measure the success of law enforcement, and identify road sections needing tighter load control.

Understandably, WIM stations are expected to supply information on the above-mentioned percentage of overloading. They do so, routinely. Unfortunately, the figures are burdened by considerable errors, particularly when the loading is undertaken very close to the permitted limits. To see the reason clearly, imagine an extreme situation when all trucks are loaded by an infinitesimally small amount under the limit. The true percentage of overloading is thus zero. Further imagine that all those trucks

are now weighed on a 99,999 % accurate scale. Owing to the small error of the scale some trucks would register above the limit – roughly speaking about one-half of them. The percentage of overloading determined by the scale would thus be around 50 % – a huge error despite the high accuracy of the scale.

Even a well-calibrated WIM cannot prevent the above phenomenon – no scale can. Unfortunately, due to the large differences between static and dynamic axle loads, WIM commits considerable errors even when the loading is relatively far from the allowed limit.

As in the case of ESAL, the estimated percentage of prosecutable (that is, over-grace) overloading that is derived from corrected axle loads is closer to reality. Yet, in the current practice, the percentage of prosecutable overloading is evaluated from adjusted WIM-measured axle loads.

CALIBRATION OF WIM DATA

WIM measurements are susceptible to many influences. Apart from dynamic forces from passing wheels the following influences are reflected in WIM measurements:

- Levelness of the road surface in WIM’s vicinity
- Road surface quality and firmness of the road
- Road crossfall
- Mix of vehicles in the traffic stream
- Condition and suspension characteristics of individual vehicles
- Passing speed
- Passing discipline, that is, lateral position of the wheels on sensor
- Quality of WIM installation
- WIM site maintenance
- Environmental effects such as cross wind, moisture and temperature variations
- Settings of WIM sensor sensitivity
- Internal signal-processing algorithms implemented in the WIM electronics

The above factors combine and interact, particularly when vehicles travel at high speeds.

To take all the above factors into consideration and produce a reasonably good imitation of static axle-loads is an art that has not yet been mastered.

Calibration is accomplished by adjusting the sensitivity (gain) of WIM sensors. The adjustments are to be done periodically, by means of hardware, software, or both. Two adversaries usually hamper the calibration effort: practicality and cost.

A large sample of vehicles from the traffic stream on a WIM site should be accurately weighed, axle-by-axle, for this purpose. The sample should be representative of the actual vehicle mix that is present on the road during various periods, such as agricultural seasons, school and religious holidays, days of the week and hours of the

day. Obtaining such a sample is very expensive and requires huge effort – thousands of vehicles need to be periodically weighed, axle by axle, often on remote WIM sites with no static weighbridge in the vicinity. This makes the method impractical.

Nevertheless, smaller random samples of vehicles have been taken from the traffic stream on several occasions and the data processed both for research and practical purposes. One of these exercises (BKS 2002) took place in November 2001 at the Midway weighbridge situated on the N3 national toll road near Estcourt. There are six WIM stations on a 415 km toll section of the N3, which carries heavy truck traffic between Johannesburg and Durban. About 60 % of these trucks are large six- and seven-axle combinations that travel long distances and thus pass over all six WIM stations. For one week, as many six- and seven-axle trucks as practically possible were randomly selected and weighed at the Midway weighbridge, their tonnage recorded and averages evaluated for each direction. At the same time the average tonnages for six- and seven-axle trucks were obtained from all six WIMs. A ratio of static tonnage over WIM tonnage was calculated for each WIM and each direction. The twelve adjustment factors thus derived have been used since. On the N3 the actual adjustment is done by software – each raw axle load is multiplied by the appropriate adjustment factor before the WIM data are further processed and interpreted.

One should realise that the factors obtained by this method have a limited lifespan. When a WIM sensor has been replaced, or the road in its vicinity deteriorated and/or was rehabilitated, the adjustment factor is no longer applicable and the tedious and expensive exercise has to be repeated.

The currently most popular and widely adopted calibration technique uses a fully loaded two-axle truck whose true static axle loads (usually about 6 t + 9 t) are determined on a static weighbridge. This truck is then driven over a WIM sensor, approximately 20 times. The runs are repeated with speeds ranging from 5 km/h to 100 km/h. An adjustment factor k is calculated from the ratio of total true mass over total WIM-registered mass. The standard deviation of WIM-measured axle loads is also evaluated. If the factor is close to unity (say, within 0,95–1,05) and the standard deviation is small (say, less than 500 kg) then the WIM installation is regarded to be in good working order. Yet, the factor itself is not applied to measured axle loads. The procedure thus becomes *verification* rather than calibration.

For practical reasons it is preferable to keep the setting of WIM sensitivity constant for as long as possible, to ensure a steady recording reference. As long as there is such

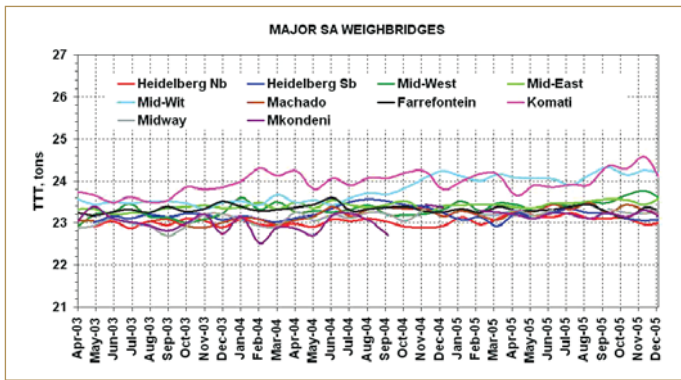


Figure 3 Monthly averages of TTT (truck-tractor tonnage of big overloaded trucks) determined by static weighing at the major permanent weighbridges in South Africa

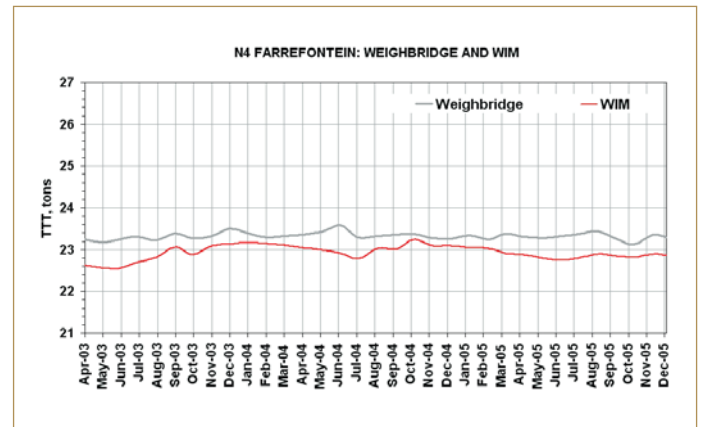


Figure 4 The TTT trends of the N4 Farrefontein weighbridge and its screening WIM scale

a reference the measured axle loads can easily be adjusted with retrospect, if needed. For this reason the adjustment factors k are not applied to the WIM hardware when they are close to unity. When they are not, a more resolute action than adjustment of measured axle loads is usually required.

COMPLEXITY OF WIM INSTALLATION AND MAINTENANCE

Installation and maintenance of WIM stations is a highly specialised job that requires particular skill and extensive experience, which most WIM-data users do possess. The current situation on the SA market reflects a logical solution to this problem: WIM users buy information rather than equipment. Several WIM service providers supply WIM data and information on a contractual basis. In principle, the contract stipulates quality of data, checking and validation procedures, time when data are due, and a remuneration formula.

This arrangement and a competitive environment have resulted in rational pricing. For example, regular supply of good-quality WIM data from a four-lane freeway, where WIM sensors are in the outer lanes and inductive loops in all lanes, costs approximately R25 000 per station per month, depending on the number of stations in the contract and their geographic position.

In most WIM information-supply contracts the rules of data validation and payment formula are tied together. On receipt of data, usually within the first seven days of the month, the WIM user or his agent scrutinises the data files using locally developed computer programs such as Trafbase or Golem. Illogical and otherwise defective data identified by the computer are rejected immediately. The remaining good data are evaluated and interpreted. Traffic and loading characteristics thus obtained are compared with historical and expected patterns. Unexplained deviations from these may lead to further rejection.

In principle, the payment formula for a continuous WIM data supply is

based on the so-called *extent of good records* (EGR), which involves both the extent and quality of WIM data. EGR is the product of two percentages: the percentage of time for which data are available, multiplied by the percentage of good (that is, not-rejected) vehicle records. Due to competence of WIM service providers the magnitude of EGR currently being achieved in South Africa is high – around 95 %.

TRUSTWORTHINESS OF WIM INFORMATION

Although WIM data are checked, validated and scrutinised from the quality point of view, one is never quite sure about the degree to which the traffic loading derived from WIM measurements represents the actual situation. With all the precautions taken the reliability and trustworthiness of WIM results remain a concern.

To tackle the above problem a WIM auditing method was developed by the author. The method concentrates on trends in the so-called truck-tractor tonnage (TTT) of large overloaded trucks. Large trucks are those with six or more axles. The truck is overloaded when any legal loading limit is exceeded. The truck-tractor (also called 'horse') must have two axle units – one steering and two driving axles.

The TTT parameter proved in practice to be remarkably stable. With an exception or two, figure 3 shows that there is little variation from weighbridge to weighbridge, and from month to month, in the TTTs obtained at ten static weighbridges – the ten curves are flat and form a relatively narrow band.

One would expect a WIM operating near a weighbridge to show a similar trend – a flat curve somewhere between 23 t and 24 t.

With a well-calibrated and properly working WIM this is usually the case; see figure 4.

However, there are exceptions. The Roosboom WIM (on the N3 national toll road, southbound) was behaving strangely and inexplicably for a long time. The TTT trend plotted retrospectively revealed a cyclic pattern with peculiar troughs in winter months. The concessionaire decided to

perform accurate deflection measurements and a detailed geotechnical investigation on the concrete pavement at the WIM site. The results indicated the presence of large voids under the concrete slabs. After the cavities were eliminated by means of grouting in August 2005 the TTT value returned to the expected magnitude of about 23 t and has stayed there since, as is apparent from figure 5. For comparison purposes the TTT trend obtained at the Midway weighbridge that is situated next to the N3 national road some 50 km north of the Roosboom WIM station, is also plotted.

Another WIM with suspicious measurements was on the N1 national road near Polokwane. Its TTT trend plotted retrospectively is shown in figure 6. Detailed pavement inspection and tests done in August 2004 revealed ingress of water into pavement base, pavement failure in the vicinity of both WIM sensors, and loose frames supporting the sensors. In November 2004 the sites were reconstructed in flexible pavement structure to a good condition. After the reconstruction the TTT values returned to normal and the trend has stabilised.

The experience shows that most of WIM problems are caused by poor riding quality, pavement deterioration and distress. These may be due to ageing and deterioration under traffic or be induced by faulty WIM installation. Grooves cut into the road surface to accommodate inductive loops and their feeders cause the pavement to crack. The crack itself is not a problem. However, when not properly sealed the cracks allow water to penetrate into the pavement base. Rutting, longitudinal deformation and further cracking result in a failure of the pavement. Unevenness of pavement is always detrimental to WIM accuracy. However, when a sensor frame becomes separated from the road the situation becomes critical – the WIM measurements become erratic and unusable.

Interestingly, under normal circumstances the TTT seems to reflect the effect of law enforcement. On sites with intensive policing against overloading the values are

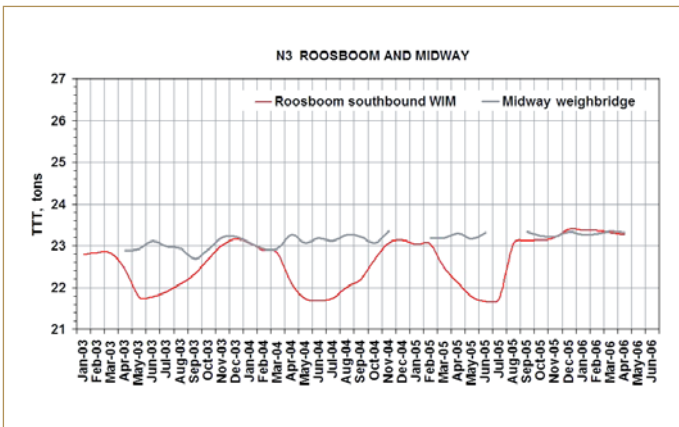


Figure 5 The TTT trends of the N3 Roosboom WIM and Midway weighbridge

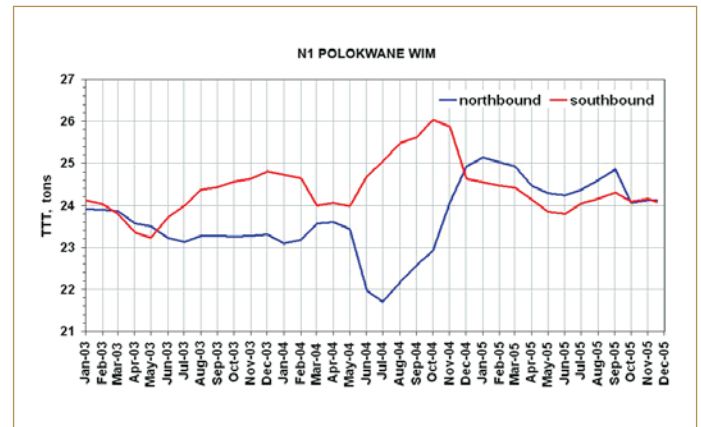


Figure 6 The TTT trends of the N1 Polokwane WIM

around 23 t, whereas on truck routes with sporadic or non-existent law enforcement the TTT values may be as high as 25 t. If the WIM works correctly, high values of TTT indicate the need for a more vigorous police intervention to control overloading.

Regular monitoring of the TTT trends has proved to be a relatively simple and effective diagnostic. Whenever the trend displays unusual behaviour it is worthwhile to inspect the WIM site thoroughly, particularly the quality of pavement structure adjacent to the WIM site and the bond between WIM frames and the road.

SITE SELECTION

The selection of a WIM site requires experience and foresight. Once the client has identified the stretch of road from which he needs data, the WIM service provider decides on the actual position of the station. It should be on a straight and level section with very sound pavement structure. Other important factors have to be considered as well. The lane discipline should be good, even if rumble strips, guardrails or other devices are to be installed to make vehicles travel over the sensor. Good cell phone reception is important for remote checking, testing and data extraction. The station should not be vulnerable to flush floods; it should be protected against lightning, vandalism and theft. The usual targets are solar panels, batteries, cables and even loop wires. While breaking into housing, thieves often seriously damage or destroy the equipment. The repairs and replacements are costly and valuable data are lost. The best solutions implemented to date are very strong steel housings with hidden locks, the use of mains instead of solar power whenever possible, and selecting places where activities of criminals would be noticed by the public.

ROAD AGEING AND DETERIORATION

From all the adverse factors mentioned above the poor condition of pavement is the

most critical. The majority of WIMs are operating on flexible-pavement roads. Because of its bitumen content asphalt behaves as a visco-elastic material. A surface that was level and smooth at the time of installation does not remain in that condition indefinitely – after a few years, or sometimes only months, rutting, cracking, and longitudinal undulation appear. These have a detrimental effect on the accuracy of WIM data.

Detection and measurement of rutting is relatively simple – a 3 m long straight edge placed across the lane, and a calibrated wedge pushed into the gap between the edge and road surface is all that is needed. To measure the road deformation in the longitudinal direction is a much more complicated task which requires special and costly instrumentation. To alleviate this problem, technicians sometimes use a simple method: they drive a vehicle with hard suspension – a bakkie with tyres inflated to a high pressure – at 100 km/h in the lane that contains the WIM sensor. They start some 500 m upstream and continue for about 700 m. While perceiving the vibration of the vehicle the driver's body works as an 'informal accelerometer'. With a little practice most people can consistently rate the smoothness of the surface from a very poor 1 to an ideal 10.

However subjective and unscientific this method may be, it is surprisingly effective. The transverse and longitudinal deformations tend to appear together. If excessive rutting is accompanied by a bumpy ride the combined evidence is usually strong enough to suggest that the road owner should improve the surface. If not, then the service provider should be exonerated from his responsibility for accurate WIM data.

CONCLUSION

Notwithstanding the problems mentioned above, WIM measurements of axle loads provide useful information appreciated by both pavement engineering and law enforcement practitioners.

However, these practitioners have to take cognisance of WIM limitations, particularly its inherent inaccuracy. Even with good calibration and regular maintenance WIM-measured axle loads are burdened with considerable and significant errors. The characteristics derived from these measurements, such as average ESAL per axle, axle group, or heavy vehicle, may be suitable for a comparison of alternatives and pointing out the order of magnitude. Unfortunately, they are not good enough to support legal arguments about the exact percentage of prosecutable overloading, or the proportion of ESAL generated by overloaded heavy vehicles.

Once the above facts have stoically been accepted, the main obstacle in the competent use of this technology is removed. Yet, WIM installations are complicated and vulnerable. Their performance should be monitored critically and regularly. While small deviations from expected patterns are no reason for panic, considerable irregularities should always be taken seriously and serve as a signal for proper investigation of the site.

WAY AHEAD

Further proliferation of WIM technology could be stimulated in the future by its application in new fields. The possibilities include the following.

A great impetus could come from modernised legislation permitting high-precision slow-speed dynamic weighing of vehicles to be used for prosecution purposes.

WIM accuracy can be improved considerably by reducing the speed of weighed vehicles. When this is not possible the use of multiple sensors may be the answer. Improvement and standardisation of calibration techniques by road authorities is long overdue. With a large number of WIM stations in operation, the use of a dedicated fleet of accurately loaded calibration vehicles with sealed load may be economically viable. In this scenario specially instrumented calibration vehicles simulating various types of loading could also be an option, particu-

larly with their high cost being spread over many projects and users.

In a futuristic view WIM is likely to play an important role in the ultimate road-pricing scenario, when road travel may continuously be metered and users presented with monthly accounts, according to the type of vehicle, number and length of trips done, time of travel, and load carried.

ACKNOWLEDGEMENTS

The author hereby expresses his gratitude to the following for the permission to use data from their WIM stations:

- South African National Roads Agency Ltd
- Northern Toll Road Venture (NTRV), the concessionaire of the N1 toll road
- N3 Toll Concession (N3TC), the concessionaire of the N3 toll road
- Trans African Concessions (TRAC), the concessionaire of the N4 Maputo Corridor toll road

REFERENCES

- ASTM E1318 – 02 (2002). Standard specification for highway weigh-in-motion (WIM) systems with user requirements and test methods. American Society for Testing and Materials, ASTM International, USA.
- BKS Report 2002. *Continuous weighing of six- and seven-axle*

trucks at the Midway traffic control centre from 22 to 28 November 2001. 2nd ed. Pretoria: BKS.

- Schildhauer, C. 1999. South African standard: Traffic data collection format. Version 1.01. Pretoria: Department of Transport.
- Slavik, M. 1998. Weighing of trucks in motion: calibration of equipment and correction of measurements. *Proceedings of the 4th International Conference on Managing Pavements*. Durban, South Africa, 1:68–82.
- Slavik, M. 2004. Correction of WIM measurements by the SLIMAX method. *Proceedings of the 8th International Symposium on Heavy Vehicle Weights and Dimensions*. Misty Hills, South Africa.