POST-CALIBRATION AND QUALITY MANAGEMENT OF WEIGH-IN-MOTION TRAFFIC DATA

by

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Declaration

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Abstract

Weigh-in-motion (WIM) scales are installed on various higher order South African roads to provide traffic loading information for pavement design, strategic planning and law enforcement using a scientific approach. The two most respected international guideline documents for WIM systems are the American ASTM E1318 Standard and the COST 323 European Specification, yet neither are fully suited to be applied to local WIM systems.

The author developed a post-calibration method for WIM data, called the Truck Tractor (TT) Method, to correct the magnitude of recorded axle loads in retrospect. It incorporates a series of powerful data quality checks. The TT Method is robust, accurate and adequately simple to be used on a routine basis.

The TT Method uses the truck tractor loads of articulated 6- and 7-axle trucks with single steering- and double driving axles – these vehicle are called Eligible Trucks. Only Eligible Trucks with average axle loads between 6.5 t and 8.5 t are used in the calibration process – these vehicles are called Selected Trucks. A calibration factor, k_{TT}, is determined using a fully automated iterative procedure, and multiplied with all axle load measurements to produce data for which the average truck tractor load of Selected Trucks, T_{TT}, is equal to 21.8 t. The TT Method can be used for WIMs in various operating environments and is not sensitive to the extent of miss-calibration of a WIM, clipping of sensors owing to poor lane discipline or different extents of loading on different routes.

The TT Method includes a series of data quality checks that can be used on a routine basis. They are summarised as follows:

- The standard deviation of truck tractor loads for Selected Trucks, S_{TTT}, should always be below 2.0 t, but preferably below 1.9 t.
- The standard deviation of front axle loads for Selected Trucks, S_{FTT}, should always be below 0.9 t, but preferably below 0.8 t.
- The post-calibration factor from the TT Method, k_{TT}, should be between 0.9 and 1.1. The factor for any month should not deviate by more than 3% from the moving average of the previous five months.
- The average of front axle loads of Selected Trucks, F_{TT}, should be between 5.6 t and 6.6 t; the exact values are influenced by load transfer between the steering and driving axles.
- A procedure was formulated using the Front axle / Truck tractor Ratio, FTR, to identify the percentage of Eligible Trucks that in all probability clipped the sensor. The percentage of these records must be below 10 %, but preferably below 6 %.

The TT Method has the potential to significantly improve WIM data collection in South Africa. The calibration module of the TT Method, i.e. the procedure to calculate k_{TT}, has already been accepted by SANRAL. Most of the data quality checking concepts associated with the TT Method were also accepted, although their threshold values are still being refined.

Opsomming

Weeg-in-beweging ("weigh-in-motion", WIM) skale word op talle hoë orde paaie in Suid-Afrika gebruik om op wetenskaplike wyse verkeersinligting te verskaf wat gebruik word vir plaveiselontwerp, strategiese beplanning en wetstoepassing met betrekking tot oorlading. Nie een van die twee vooraanstaande internasionale riglyne vir WIM sisteme, die ASTM E1318 Standaard en die COST 323 Europese Spesifikasie, is in geheel geskik vir Suid-Afrikaanse kondisies nie.

Die outeur het 'n unieke kalibrasie metode, genaamd die TT Metode, ontwikkel wat 'n reeks roetine kwaliteitsbeheertoetse vir WIM data insluit. Die TT Metode is eenvoudig, akkuraat en toepaslik vir 'n wye verskeidenheid WIM sisteme in Suid-Afrika.

Die massa van trekkers van geartikuleerde 6- en 7-as vragmotors met enkel stuur- en dubbel dryf-aste en 'n gemiddelde asmassa tussen 6.5 en 8.5 ton (ook genoem Geselekteerde Vragmotors) word as verwysingsmassa gebruik. 'n Iteratiewe prosedure word gevolg vir die bepaling van die kalibrasie faktor, k_{TT}. Dieselfde faktor word met alle asmassas in die data vir die analise periode vermenigvuldig, met die einddoel dat die gemiddelde trekker massa van die Geselekteerde Vragmotors, T_{TT}, gedryf word na die teikenwaarde van 21.8 ton. Die TT Metode is ewe toepaslik ongeag die tipiese belading van trokke op 'n roete, hoe goed die WIM sisteem oorspronklik gekalibreer was of hoe goed laandissipline by die WIM sensor is.

Die kwaliteitsbeheertoetse kan op 'n roetine basis toegepas word as deel van die uitvoering van WIM kalibrasie prosedure, en word soos volg saamgevat:

- Die standaard afwyking van trekker massas van Geselekteerde Vragmotors, S_{TTT}, behoort altyd laer as 2.0 ton, maar verkieslik laer as 1.9 ton te wees.
- Die standaard afwyking van voor-as massas van Geselekteerde Trokke, S_{FTT}, behoort altyd laer as 0.9 ton, maar vekieslik laer as 0.8 ton te wees.
- Die kalibrasiefaktor, k_{TT}, moet verkieslik tussen 0.9 en 1.1 wees, en mag nie met meer as 3 % van die gemiddelde k_{TT} vir die voorafgaande vyf maande verskil nie.
- Die gemiddeld van voor-as massas van Geselekteerde Vragmotors, F_{TT}, behoort tussen 5.6 ton en 6.6 ton te wees. Die presiese waarde hang af van die mate waartoe gewig tussen die voor-as en dubbel dryf-as oorgedra word weens dinamiese effekte op die trekker.
- Die verhouding tussen die voor-as en dubbel dryf-as, bekend as die FTR, kan gebruik word as 'n aanduiding of 'n trok weens swak laandissipline slegs gedeeltelik oor die WIM sensor gery het. Die persentasie gedeeltelike metings moet laer as 10%, maar verkieslik laer as 6 % wees.

Die TT Metode het die potensiaal om die insameling en kwaliteit van verkeersdata deur middel van WIM sisteme noemenswaarding te verbeter. Die kalibrasie module van die TT Metode, m.a.w. die prosedure om k_{TT} te bereken, is reeds deur SANRAL aanvaar. Die meeste van die kwaliteitsbeheerkonsepte wat met die TT Metode gepaard gaan is ook aanvaar, maar die drempelwaardes hiervoor word nog verfyn.

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The author has been actively involved with the analysis and interpretation of WIM data on major toll road projects over the past eight years. The research presented in this thesis was conducted primarily over the past three years. Some of the research was project specific, whilst some was done independently using the available data collected for toll concessionaires and SANRAL.

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Glossary

ANPR	–	Automatic Number Plate Recognition
ASTM	–	American Society for Testing and Materials
Caltrans	–	California Department of Transport
C-line	–	Minimum FTR threshold, to identify WIM sensor clipping (TT Method)
COST	–	Co-Operation in Science and Technology
CSIR	–	Council for Scientific and Industrial Research
Eligible Truck	–	Typical 6-axle articulated truck or 7-axle interlink truck with a single steering and double driving axle on the truck tractor (TT Method)
F	–	Front axle load (used in FTR and TT Methods)
F17 format	–	Weighbridge data format available the with Trafman operating system
F30	–	Front axle load of vehicles in higher 30% window (FTR Method)
FEHRL	–	Forum of European National Highway Research Laboratories
FFF	–	Front axle load used in FFF Method
FFF Method	–	WIM calibration method using front axle load of 6- and 7-axle trucks
FHWA	–	Federal Highway Administration
FiWi	–	FEHRL institutes WIM initiative
FTR	–	Front axle / Truck tractor Ratio
FTR Method	–	WIM calibration method using the FTR concept
FTR30	–	FTR of Selected Trucks (TT Method)
F_{TT}	–	Front axle load of Selected Truck (TT Method)
GVM	–	Gross Vehicle Mass
IRI	–	International Roughness Index
k_{FTR}	–	WIM calibration factor based on the FTR Method
k_{TT}	–	WIM calibration factor based on the TT Method
k_{WL}	–	WIM calibration factor based on the Weighbridge-Linked Method
LCC	–	Load Control Centre
LSWIM	–	Low-Speed Weigh-in-Motion
NCHRP	–	National Cooperative Highway Research Program
Post-calibration	–	Retrospective calibration of WIM data after collection (as opposed to calibration of equipment before data collection)
RSA format	–	South African National standard traffic data format
SANRAL	–	South African National Roads Agency Limited
s_e	–	Standard Deviation of WIM Error
Selected Truck	–	Eligible Truck with average axle load between 6.5 t and 8.5 t
S_{FTT}	–	Standard deviation of front axle loads of Selected Trucks
S_{TTT}	–	Standard deviation of truck tractor loads of Selected Trucks
T	–	Truck tractor load (used in FTR and TT Methods)
T30	–	Truck tractor load of vehicles in higher 30% window (FTR Method)
TMH	–	Technical Methods for Highways
TT Method	–	Truck Tractor Method
T_{TT}	–	Truck tractor load of Selected Truck (TT Method)
VTT	–	Technical Research Centre of Finland
WAVE	–	Weigh-in-Motion of Axles and Vehicles for Europe
WIM	–	Weigh-in-Motion
δ	–	Confidence interval for WIM error, used in the COST 323 Specification
π_0	–	Minimum confidence levels, used in the COST 323 Specification

Table of Contents

List of Figures

List of Tables

List of Appendices

1 INTRODUCTION

1.1 Background

After some 40 years of existence, the weigh-in-motion (WIM) scale is still the only technology that can estimate the static axle loads of moving vehicles. Different types of WIM technology are used, of which bending plates, capacitive sensors and strip sensors (e.g. piezo electric sensors) are the most common. Load cell technology is used for low-speed WIMs (LSWIM), and the instrumentation of existing road bridge structures for the purpose of weighing is one of the most recent additions to WIM technology.

Large sums of money are spent annually on WIM data collection for statistical purposes and law enforcement, yet the collected data are often inconsistent and the derived pavement loading characteristics are not always realistic. WIM systems often produce anomalies that cannot be satisfactorily explained even by highly experienced professionals. This is one of the reasons why there is still no consensus within the industry on the physical requirements for a WIM system, the calibration of data, and data quality checks that can be used to manage contractor performance and identify or eliminate erroneous or dubious weigh records. In practice, agencies and WIM vendors are still experimenting with variations (and often simplifications) of the two most commonly recognised WIM Standards, ASTM E1318 and COST 323, whilst enhancements contributed by researchers are often highly complex and consequently under-utilised in practice.

The users of WIM data are often ignorant of the inherent inaccuracies of WIM systems. In the absence of industry norms, data quality is consequently not as good as it could be. Miss-calibration and the imprecision of WIM further aggravate the problem. Without proper guidance, poor WIM data can be misinterpreted and miss-used, and may result in imbalances in pavement design and overload control efforts. The credibility and value of WIM systems are thus in jeopardy. Much of the problem relates to the difficulty determining the correct calibration factors for WIM systems and the random error component that remains even if the systematic error is eliminated.

WIM calibration is performed either by adjusting the sensitivity of the equipment by a factor, or by multiplying all axle load measurements from already collected WIM data with a factor to produce acceptable results. The aim of this multiplication factor is to suppress systematic

WIM error. It is generally referred to as the calibration factor or k-factor. WIM errors are different for different types of vehicles travelling at different speeds. Whilst a single calibration factor is generally applied to all axle load measurements, some methods have been developed internationally whereby calibration factors are varied based on e.g. the type of axle, type of vehicle or speed. Given the highly variable nature of WIM error, the methods to correct it for all vehicles in the traffic stream are often inadequate or so complicated that many practitioners do not use them. This complicates the objective assessment of the quality of loading data on a routine basis.

1.2 Problem Statement

Whist WIM systems are installed to provide a scientific basis for pavement design, strategic planning and law enforcement, they sometimes create uncertainty and dispute. This is not only due to the inherent inaccuracy of WIM, but also inadequate data quality management, improper calibration methods and the misinterpretation / misuse of WIM readings. The absence of procedures to render WIM data consistent, reliable and accurate undermines its value.

1.3 Objective

The objective of this thesis is to develop an accurate, robust WIM calibration method with practical data quality checks for routine quality control that can be applied to a wide range of WIMs in South Africa. The procedure must allow for retrospective calibration of WIM data after it has been collected (as opposed to on-site calibration of equipment), and it is therefore referred to as post-calibration.

2 LITERATURE SURVEY

2.1 International WIM Standards

Two primary international standards are available for the calibration of WIM systems. They are the ASTM E1318 Standard [1] that was developed in the USA, and the COST 323 European WIM Specification [2] that was developed under the leadership of FEHRL (Forum of European National Highway Research Laboratories). Several variations and refinements of the ASTM Standard were investigated and are used by different States within the USA [3]. Even though COST 323 is not a standard as such, it has become the de-facto Standard for European countries [4]. These two documents also have also had a major impact on South African WIM calibration practices thus far.

2.1.1 ASTM International

ASTM International, originally known as the American Society for Testing and Materials (ASTM), is one of the largest voluntary standards development organisations in the world. The ASTM E1318-02 Standard Specification for Highway Weigh-in-Motion (WIM) Systems [1], last revised in 2002, provides a performance based specification for the accuracy of WIM systems. It deals with three concepts with regards to WIM operation:

- Performance requirements to which a WIM must conform;
- User requirements to ensure an operating environment where the WIM can achieve the required performance; and
- Test methods for WIM system performance.

Four functional types of WIMs were identified in terms of performance requirements for typical applications:

- ***Type I*** is a typical data collection WIM system where the wheel loads in both wheel paths are measured. Operating speeds may range between 16 km/h and 130 km/h. The user is also allowed to use the measurements from one end of the axle (i.e. from half-lane sensors) to estimate axle loads.

- ***Type II*** is the same as Type I with the exception that a speed range of 24 km/h to 130 km/h must be accommodated and individual wheel loads (i.e. the respective ends of an axle) need not be known.
- ***Type III*** is used to identify potentially overloaded vehicles in dedicated screening lanes or in a normal highway lane. They are typically used in combination with static weighbridges where accurate weighing and prosecution of overload offenders takes place. Operating speeds may range between 16 km/h and 130 km/h, and wheel loads must be recorded.
- ***Type IV*** is a low-speed WIM (LSWIM) where operating speeds are limited to between 3 km/h and 16 km/h, and is intended to be used for prosecution of overload offenders. Few countries in the world allow prosecution based on WIM measurements, and it is similarly prohibited in South Africa.

The functional performance requirements for the defined WIM Types were developed taking cognisance of the intended application of the WIM and its operating environment. Table 2-1 below shows the tolerances of WIM error. The stated accuracies must be maintained for an ambient temperature range of -28 ºC to 50 ºC.

Table 2-1: ASTM E1318 Functional Performance Requirements

Function	Tolerance of WIM error for 95 % Probability of Conformity				
	Type I	Type II	Type III	Type IV	
	Error	Error	Error	Minimum	Error
Wheel load	± 25 %	n/a	± 20 %	2.3 t	± 100 kg
Axle load	± 20 %	± 30 %	± 15 %	5.4 t	± 200 kg
Axle group	± 15 %	± 20 %	± 10 %	11.3 t	± 500 kg
Gross Vehicle Mass	± 10 %	± 15 %	± 6 %	27.2 t	± 1100 kg

Minimum test loads were introduced for Type IV systems as smaller loads are usually not a concern with regards to law enforcement.

The ASTM specification makes it clear that the performance of the WIM system depends uniquely upon the quality of the sensors and their prevailing operating environment. The quality of performance is directly related to the site conditions. So-called user requirements were thus formulated for the portion of the traffic lane 60 m upstream and 30 m downstream of the WIM system. The following criteria must be adhered to:

- Horizontal radius > 1.7 km
- Gradient < 2 % for Type I, II and III systems

- Cross slope < 3 % for Type I, II and III systems
- Gradient and cross slope < 1% for Type IV systems
- Lane width between 3.6 m and 4.3 m
- Level to within 3 mm using a 6 m straight edge and prescribed measurement method

The levelness test procedure entails sweeping movements over the pavement using a 6 m straight edge whilst checking whether a circular disc with diameter of 150 mm and thickness of 3 mm can pass under the straight edge. The sweeping movements are executed from both edges of the WIM lane, keeping the end of the straight edge furthest from the WIM in a fixed position and sweeping it across the lane until it touches the other side of the lane. The starting positions for sweeping movements are predefined, and are shown below:

Table 2-2: ASTM E1318 Levelness Check Starting Positions

Lane Edge	Longitudinal Distance from Center of WIM Sensors (m)													
Right	6	9	13	18	23	28	33	38	43	48	53	58	62	
Left		6	11	16	21	26	30	35	40	45	50	55	60	65

No limitations are placed on the type of pavement that must be used in conjunction with WIM systems, but it is mentioned that consideration should be given to providing a 90 m long continuously reinforced concrete pavement or jointed concrete pavement with transverse joints no more than 6 m apart.

A rigorous test method for type approval is provided by the E1318 Standard, which is used to certify that a particular WIM system can achieve the functional performance requirements shown in Table 2-1 under excellent operating conditions. It uses two pre-weighed test trucks (2-axle and 5-axle) in combination with 51 vehicles selected from the traffic steam. These procedures are performed by the providers of WIM equipment and data collection services.

A calibration method is also provided by the E1318 standard to determine whether a WIM in operation achieves the required accuracy. Recalibrations must be done at least annually, and also following any significant maintenance, relocation or if data patterns are suspect. The calibration method uses a pre-weighed two-axle truck and a five-axle articulated truck, each loaded to at least 90 % of their registered capacities. Three or more passes are made over the WIM by each truck at the representative speed of truck traffic at the site, a higher speed and a lower speed respectively. The higher and lower speeds shall differ by at least 30 km/h. Passes must also be made such that the wheels travel over the left side, center and right side of a sensor. The accuracy of the WIM sensor is then verified against the requirements described in Table 2-1.

2.1.2 European COST 323 Specification

The COST 323 Management Committee, with representation in 18 European countries, developed the COST 323 European WIM Specification [(2)] of which the latest version was published in 1999. Appendix I of that report contains a summary of the specification, and is meant for its practical application by common users of WIM systems and data.

The specification considers three classes of WIM sites that are defined in terms of rutting, deflection and evenness, and the threshold values to which the pavement should conform from 200 m upstream to 50 m downstream of the WIM system are given in Table 2-3 below.

Table 2-3: COST 323 Classification and Criteria of WIM Sites

Test	Pavement	Description	Thresholds – WIM Site Classes: I Excellent	II Good	III Acceptable
Rutting (3 m beam)	All	Rut depth (mm)	≤ 4	≤ 7	≤ 10
Deflection (quasi-static) (13 t axle)	Semi-Rigid	Mean deflection (10^{-2} mm) Left/right diff (10^{-2} mm)	≤ 15 ± 3	≤ 20 ± 5	≤ 30 ± 10
	All bitumin	Mean deflection (10^{-2} mm) Left/right diff (10^{-2} mm)	≤ 20 ± 4	≤ 35 ± 8	≤ 50 ± 12
	Flexible	Mean deflection (10^{-2} mm) Left/right diff (10^{-2} mm)	≤ 30 ± 7	≤ 50 ± 10	≤ 75 ± 15
Deflection (dynamic) (5 t load)	Semi-Rigid	Mean deflection (10^{-2} mm) Left/right diff (10^{-2} mm)	≤ 10 ± 2	≤ 15 ± 4	≤ 20 ± 7
	All bitumin	Mean deflection (10^{-2} mm) Left/right diff (10^{-2} mm)	≤ 15 ± 3	≤ 25 ± 6	≤ 35 ± 9
	Flexible	Mean deflection (10^{-2} mm) Left/right diff (10^{-2} mm)	≤ 20 ± 5	≤ 35 ± 7	≤ 55 ± 10
Evenness	All	IRI (m/km)	0 – 1.3	1.3 – 2.6	2.6 – 4.0
		APL (SW, MW, LW)	9 – 10	7 – 8	5 – 6

The APL is a device developed in France, consisting of two single wheel trailers and operating at 72 km/h, which measures the longitudinal road profile. The rating quantifies the logarithm of the energy dissipated for small, medium and large wavelengths (SW, MW and LW).

In Table 2-3, the rutting and deflection values are given for a temperature below or equal to 20 ºC and suitable drainage conditions.

It should be noted that recent European trends are to use arrays of strip sensors (e.g. piezo-electric sensors) for weighing of axles in favour of wide sensors (e.g. bending plates or capacitive sensors) that are commonly used in both the USA and South Africa. The rutting thresholds given in Table 2-3 may therefore be unsuitable for wide sensors that cannot follow the profile of the road. The deflection thresholds are also based on pavements that are designed to sustain European climatic conditions – pavements in South Africa have typical deflections of between 0.2 mm and 0.4 mm under a 40 kN load (5).

Different WIM calibration procedures are proposed, including the use of pre-weighed calibration trucks, instrumented calibration trucks and auto-calibration. The calibration truck method is similar to the accuracy verification process (see discussion below), but COST 323 states very specifically that the use of a single vehicle with only one load case is not recommended.

The concept of automatic self-calibration was initially developed in France (4) and makes use of characteristic vehicles of which the loading properties are known. When such vehicles are identified in the traffic stream their recorded loads are used to determine whether they corroborate the expected loads. The principle is to fit a moving average of the characteristic vehicle axle loads on the target values known by experience (7). A good prior knowledge of the site-specific traffic composition and statistics of true axle and vehicle loads are thus required for self-calibration.

The focus of the COST 323 standard is on accuracy verification rather than calibration. Three different Test Plans are described that can be used to verify the accuracy of a WIM, using one, two or four trucks. Speed variations are also introduced, and test trucks are required to make passes over the WIM at the mean truck speed, 20% higher speed and 20% lower speed.

COST 323 defines six WIM accuracy classes based on the width of the confidence interval of error tolerated for measurements of GVM, axle groups, single axles and individual axles within a group. The WIM system must be able to operate in an ambient temperature range of -20 ºC to +60 ºC. Table 2-4 summarises the accuracy classes and confidence intervals.

Table 2-4: COST 323 WIM System Accuracy Tolerances

Element	Accuracy Classes and Tolerances; Confidence Interval Width δ (%)						
	A(5)	B+(7)	B(10)	C(15)	D+(20)	D(25)	E
GVM	5	7	10	15	20	25	>25
Axle Group	7	10	13	18	23	28	>28
Single Axle	8	11	15	20	25	30	>30
Axles within Groups	10	14	20	25	30	35	>35

Class A(5) and B+(7) WIMs are highly accurate and are suitable to be used for prosecution purposes. Class B(10) WIMs may be used for pre-selection of potentially overloaded trucks at load control facilities. Class C(15) and D+(20) WIMs are suitable for detailed statistical studies, while Class D(20) and Class E WIMs should only be used for rough statistical purposes.

The confidence level associated with the specified confidence intervals depends on the type of reference loads and method of accuracy evaluation. Four categories were defined to characterise the types of reference loads:

- ***(r1) full repeatability conditions*** – if only one vehicle passes over the WIM at constant speed and carrying the same load.
- ***(r2) extended repeatability conditions*** – if only one vehicle passes over the WIM at varying speeds and with different loads.
- ***(R1) limited reproducibility conditions*** – if a small representative set of vehicles, typically between 2 and 10, travel over the WIM at varying speeds and with different loads.
- ***(R2) full reproducibility conditions*** – if a large representative sample of vehicles from the traffic stream is weighed just before or after the WIM and used for the evaluation of accuracy.

A second type of repeatability is used to characterise the time periods during which accuracy tests are executed:

- ***(I) environmental repeatability*** – if the test is limited to a couple of hours or a few consecutive days with similar temperature, climatic and environmental conditions.
- ***(II) limited environmental reproducibility*** – if the test duration is between a week and a month with varying environmental conditions, but without seasonal fluctuations.

- ***(III) full environmental reproducibility*** – if the test extends over at least a year to represent all seasonal and daily climatic and environmental changes.

The minimum required levels of confidence, π_0, associated with the respective repeatability categories are listed below:

Table 2-5: Confidence Levels, π_0, for WIM Accuracy Evaluation (%)

Test Conditions	Sample Size (n)	10	20	30	60	120	∞
(I) Environmental repeatibility	(r1) Full repeatibility	95	97.2	97.9	98.4	98.7	99.2
	(r2) Extended repeatibility	90	94.1	95.3	96.4	97.1	98.2
	(R1) Limited reproducibility	85	90.8	92.5	94.2	95.2	97.0
	(R2) Full reproducibility	80	87.4	89.6	91.8	93.1	95.4
(II) Limited environmental reproducibility	(r1) Full repeatibility	93.3	96.2	97.0	97.8	98.2	98.9
	(r2) Extended repeatibility	87.5	92.5	93.9	95.3	96.1	97.5
	(R1) Limited reproducibility	81.9	88.7	90.7	92.7	93.9	96.0
	(R2) Full reproducibility	76.6	84.9	87.4	90.0	91.5	94.3
(III) Full environmental reproducibility	(r1) Full repeatibility	91.4	95.0	96.0	97.0	97.6	98.5
	(r2) Extended repeatibility	84.7	90.7	92.4	94.1	95.1	96.8
	(R1) Limited reproducibility	78.6	86.4	88.7	91.1	92.5	95.0
	(R2) Full reproducibility	73.0	82.3	85.1	88.1	89.8	93.1

The number of measurements and the mean and standard deviation of WIM errors for each of the four test elements are required to determine whether a WIM system passes or fails the accuracy verification test. The result can be calculated using statistical formulae, or read from a series of graphs. The accuracy verification takes the combination of the mean and spread of errors into account.

A higher standard of pavement is required to achieve the higher accuracy classes, as shown in the table below:

Table 2-6: Choice of WIM Site According to Accuracy Required

Accuracy Class	Pavement Class I Excellent	Pavement Class II Good	Pavement Class III Acceptable
A(5)	+	-	-
B+(7)	+	-	-
B(10)	+	+	-
C(15)	(+)	+	+
D+(20)	(+)	(+)	+
D(25)	(+)	(+)	+
– means insufficient, + means sufficient and (+) means sufficient but not necessary			

FEHRL initiated the FiWi project during the period 2007 to 2009, of which one of the aims is to perform a general update of the COST 323 Specification and to eventually transform it into a European Standard [4].

2.2 International WIM Practices and Research

2.2.1 FHWA Handbook on Successful WIM Practices

The Federal Highway Administration (FHWA) developed a Successful Practices Handbook for the USA [8] in 1997. The document is practice orientated and shares "tricks of the trade" that were developed by state experts and vendors who have been actively involved with WIM systems over a long period of time. It deals with the construction of different types of WIM systems, their calibration and data quality assurance. The American States rely heavily on the ASTM E1318 Standard when operating WIM systems.

The California Department of Transport (Caltrans) was a prominent contributor to the successful practices handbook. A few key aspects from their contribution are highlighted below:

- The major data problem effected by installing a WIM system on a grade, say anything in excess of one percent, is the weight 'transfer' from the steering axles to the drive axles of loaded trucks.
- Caltrans requires that all WIM systems be installed in Portland cement concrete (PCC) pavements to provide roadway stability, durability, and smoothness throughout the 10 to 15 year expected equipment life.
- It is neither practical nor effective to attempt static weighing of a large sample of random vehicles from the traffic stream to calibrate a WIM system. Caltrans recommends that WIM vendors provide and use only one test truck to calibrate the WIM system. The chosen test vehicle should be the predominant truck type on the road.
- To properly diagnose, interpret, and validate data from a WIM System, the analyst must have knowledge of (1) the site's physical characteristics, (2) traffic and truck behaviour, and (3) the WIM System's vehicle passage processing.

The Minnesota Department of Transport uses an automatic system recalibration procedure for their WIM systems. The process is briefly explained as follows:

- An initial calibration is done using a 5-axle articulated calibration truck.
- The WIM system is operated for a week, and the calibrated state of the WIM system is accepted (or rejected) by visual inspection of the position of GVM peaks for empty and loaded trucks respectively.
- The collected data is used to determine typical front axle loads for the "characteristic truck" in its empty (GVM < 14.50 t), intermediate (14.50 t < GVM < 31.75 t) and loaded states respectively.
- The system recalibrates if the percentage of the difference between the average recorded and desired front axle loads is greater than a set percentage in at least two of the three GVM groups for a predetermined minimum duration and number of characteristic trucks. The average of front axle load discrepancies for the three GVM categories is used to adjust the calibration factor of the WIM system.

2.2.2 NCHRP Syntesis 386 of WIM Calibration Practices

The National Cooperative Highway Research Program (NCHRP) produced a document in 2008 that describes and evaluates current high-speed WIM system calibration practices. It comprises two major parts, viz. a thorough literature review of WIM calibration standards and current practice statements, and an online questionnaire to highway and load enforcement agencies administering WIM systems in the USA.

The synthesis confirms the ASTM E1318 Standard and COST 323 European WIM Specification as the most significant industry norms with regards to WIM calibration.

The online questionnaire was structured to gain information on three topics:

- on-site calibration using test trucks;
- calibration using vehicles of known static weight from the traffic stream; and
- calibration monitoring using WIM data and properties of the traffic stream.

Some of the key findings from the three parts of the questionnaire are summarised below:

a) Calibration using Test Trucks

- The frequency of routine calibrations varies between 6 months and 24 months, with the majority being performed every 12 months.
- The majority of agencies using test trucks for calibration consider pavement roughness, but only a quarter use objective testing methods. 15 % use the international roughness index (IRI) as an indicator, 11 % perform the 3 mm circular disc test prescribed by ASTM E1318 and the rest simulate this test in software using the pavement profile as input.
- Most agencies use fixed static scales in favour of portable scales to determine reference loads for test vehicles.
- The majority of agencies specify an air suspension for test trucks, but this is not properly enforced.
- WIMs are calibrated at the average truck speed or posted speed limit for 70 % of data collection sites and half of law enforcement sites. Multiple speeds are used to a lesser extent.
- Most agencies compute calibration factors based on mean error of GVM or axle loads. Few use the more complicated method of minimising the least square error between WIM and static axle loads.

b) Calibration using trucks from the traffic stream

- Almost all agencies managing enforcement-only WIM systems use trucks from the traffic stream to calibrate their WIMs. Most of these agencies use the static scales at the law enforcement facilities to obtain static reference weights, and the remainder use portable static scales.
- Calibrations are generally triggered by indications that there is drift in the systematic measurement error, and only one third of agencies calibrate on a routine basis.
- A sample of between 1 and 100 vehicles from the traffic stream, but typically about 40 trucks, are used for calibration.
- The majority of agencies using WIM systems for data collection only select trucks in certain classes for calibration purposes, while agencies using WIM for law enforcement mostly favour the use of random samples of trucks.
- Only about one quarter of agencies that responded indicated that they use speed-specific calibration factors.

c) Calibration through WIM data quality control

- Most Departments of Transport perform their own quality control based WIM calibration.
- With few exceptions, almost all of the agencies that responded believe that WIM data quality control can be used to identify system operational problems.
- Articulated 5-axle trucks are mostly used for quality control of loading data. The most common loading properties monitored are the average steering axle load, left/right imbalance of the steering axle, GVM for empty versus loaded trucks and GVM versus vehicle speed.
- Standard deviations of front axle load and GVM are monitored mostly by agencies using WIM systems for law enforcement.

In addition to the specific questions about the three key topics, responders were also given the opportunity to make more general comments. The following are some of the suggestions offered with reference to the question regarding urgent technical needs:

- "Develop more accurate sensors".
- "Develop better pavements in which to install sensors".
- "Create an understanding of how calibration test vehicles relate to the traffic stream".
- "Create an understanding of how pavement roughness relates to WIM accuracy".
- "Calibrate without using test trucks".
- "Attain a better understanding of the limitations of WIM data and educate the states on such limitations".
- "Identify and standardise best calibration practices".
- "Create diagnostic guidelines for calibration of WIM sites from a centralised office location".

Some negative sentiments regarding WIM systems were also noted. A few comments are summarised below:

- "Bending plates systems are no longer used owing to their required constant maintenance and their data being no better than from Type II systems".
- "Assumes data must be adequate, given that FHWA is not complaining".
- "WIM data are not being used".

- “Volume and classification data adequate, but weight data are borderline”.
- “Eliminate WIM data collection”.
- “Do only the minimum WIM data collection”.

2.2.3 WAVE

Weigh-in-Motion of Axles and Vehicles for Europe (WAVE) was a prominent and extensive research study in the late 1990’s [(8)]. It completed the work initiated in the COST 323 action. The major objectives of the study were to develop WIM calibration methods [(10)], to develop WIM systems with multiple sensor arrays [(11)] and to improve upon quality control over WIM data [(12)].

The report of Work Package 3.2 [(10)] dealt specifically with calibration of WIM systems and the intricacies of WIM error.

The report notes that dynamic axle loads may vary by ±15 % (or more) due to the unevenness of the road. The main movements of a vehicle are (1) body bounce, (2) body pitch, (3) axle hop and (4) tandem pitch, as illustrated in the figure below.

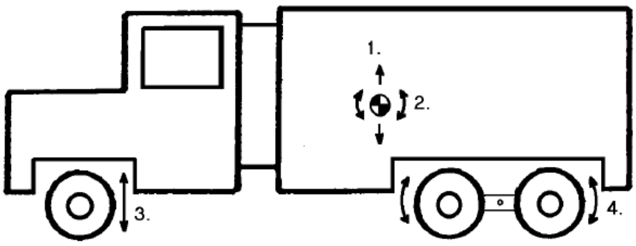


Figure 1: Dynamic Movements of a Vehicle

The dynamic loads of a vehicle are different from the static loads. The Technical Research Centre of Finland (VTT) made the first dynamic wheel load measurements in 1987. VTT uses a rigid 3-axle test truck of which the axle housings are instrumented with strain gauges and accelerometers to determine dynamic axle loads. The vehicle was made available to WAVE for research in 1997. Dynamic loads oscillate around the mean owing to body bounce and axle hop. The dynamic loading pattern differs for different vehicle speeds and loading cases. It was interesting to note that the small unevenness caused by the WIM systems tested at Lulea and Metz had a clear impact on the dynamic loading profile. Using the data from instrumented trucks, it was also confirmed that the type of truck has a noticeable impact on the apparent calibration factor that should be applied to WIM data.

Even though the performance of bending plates are usually not dependent on the ambient temperature, an investigation into the performance of PAT bending plate sensors at Lulea in December 1997 indicated that a temperature correction was necessary for temperatures below +5 ºC. PAT Germany consequently developed an appropriate temperature correction algorithm.

2.3 South African Practice and Standards

2.3.1 South African National Roads Agency

The South African National Roads Agency Ltd (SANRAL) is a prominent user of loading data from their own as well as other WIM systems. The contracts between SANRAL and various toll road concessionaires stipulate that the added cost of road maintenance over the concession period as a result of overloaded trucks may be claimed back from SANRAL. The quantification of overload claims is based on WIM data. The quality of WIM data has always been a contentious issue owing to the large sums of money involved and general uncertainty within the industry on how to provide well calibrated, credible WIM data.

In 2006 SANRAL produced a Standard Specification for Traffic Data Collection Services (13). The specification was primarily intended for data collection contracts between SANRAL and its service providers. Toll concessionaires were similarly anxious to provide acceptable data from their own WIMs and at least two of them, N3 Toll Concession (N3TC) and Northern Toll Road Venture (NTRV), incorporated the specification into their own service provider contracts in 2006.

The SANRAL Standard Specification used the COST 323 European WIM Specification as a basis for the sections on WIM data collection. It made one important qualification, which was that a single rigid three-axle truck must be used for accuracy verifications. The three axle truck is the smallest truck that allows testing of all four test elements (GVM, axle group, single axle and individual axles within a group) described by COST 323.

SANRAL lodged a large research project to revise the South African Flexible Pavement Design Method in 2008. The project also covered WIM calibration (14), and changes to the WIM calibration philosophy are currently being tested. The SANRAL Standard Specification for Traffic Data Collection is being revised based on the experience of the past three years, and indications are that at least the calibration and accuracy verification parts of the COST 323 Specification may not be retained.

The Council for Scientific and Industrial Research (CSIR) developed a procedure and software for SANRAL in 2007 to calculate of the cost of overloading on toll concessions (15). The procedure aims to compensate the concessionaire for early maintenance and rehabilitation required, and the strengthening of the pavement to carry the additional equivalent traffic caused by overloaded heavy vehicles. The model relies on WIM data to depict the axle loading on the pavement, and basic axle mass and spacing filters were used to identify obvious outliers. Until 2008, the accuracy of WIM data used in the software model was evaluated using the average front axle load of 7-axle truck-and-trailer combinations with single steering and double driving axles as a basis. WIM data was considered to be suspect if the average front axle mass of these trucks fell outside the 5.9 t to 6.4 t range. The software is currently being revised in conjunction with SANRAL's review of the WIM calibration method.

2.3.2 South African Standard Traffic Data Collection Format

Different traffic data loggers from international and local manufacturers are available in South Africa. A non-logger specific standard, commonly referred to as the RSA data format, was developed for SANRAL in 1994. The standard has been periodically updated to keep up with changing data requirements and traffic data logger capabilities. The latest version is known as Version 2.00 Issue 2006/05/05 (16).

The standard describes the data format for different types of traffic data. The data strings containing axle mass and spacing information are known as Vehicle Data Records 13 and 14. Data Record 13 is used for WIM systems where the loads from only one side of the axles are available, and Data Record 14 for WIM systems where he left and right sides of axles is measured separately. The loads of consecutive axles on a vehicle are recorded in 100 kg units and are separated in the data string by the axle spacing given in centimetres. For Data Record 14, the data strings contain pairs of axle load measurements (firstly based on the left wheel measurement, and then the right wheel measurement).

The most WIMs in South Africa are bending plates installed in the left wheel path only (i.e. half-lane sensors) and for simplicity the axle load is assumed to be double the left wheel load. The data from such WIMs are thus recorded as Data Records 13. The loads in the left wheel path are generally greater than those in the right wheel path owing to the cross-fall of the road surface and the consequent leaning of trucks towards the left. The doubling of the left wheel loads therefore results in the over-estimation of axle loads, but such pavement loading statistics are in fact appropriate for the design of the most critical part of the traffic lane.

2.3.3 F17 Data Format for Weighbridges Operated with Trafman

Magna FS developed weighbridge operating software called Trafman. The software is used at several static weighbridges owned and used for overload law enforcement by SANRAL. Trafman can be used to manage vehicle control infrastructure (traffic lights, booms etc.) and all facets of load control and law enforcement pertaining to vehicle overloading legislation. It also keeps a database of all weighing activities that took place on the static scale.

Whilst standard reports may be generated from the Trafman database, a need to create data files with the essential data from weigh records for further analysis by SANRAL and their consultants has been identified. After some preliminary development, Magna FS established the F17 Data Format towards the end of 2003, with further enhancements up until 2006 [(17)]. The F17 files contain the weighbridge identification code, date and time stamp, overload status, vehicle details, legal loading limits and static weights per axle group and Gross Vehicle Mass (GVM).

In 2006 the F17 Format was enhanced to include the dynamic axle loads from screening WIMs that are used in combination with static weighbridges to identify potentially overloaded heavy vehicles. The scalemaster at the weighbridge thus has the opportunity to link the vehicle on the static scale with its WIM counterpart using photo images taken at the WIM. The WIM axle loads are then appended to the end of the normal string of weighbridge data in the F17 data file, followed by '*' and the WIM identification number (e.g. *2). F17 files that contain weighbridge-linked WIM data are also referred to as F17* files. At some new weighbridges (e.g. Donkerhoek, Bapong and Zebetiela) the linking of WIM and weighbridge records will be done automatically using Automatic Number Plate Recognition (ANPR) technology.

3 DATA COLLECTION

3.1 Introduction

The collection of reliable WIM and weighbridge data was necessary to provide a basis for characterising WIM error and developing a new system for WIM calibration and data quality control (see thesis objective, Section 1.3).

A wealth of data from WIM systems is available in South Africa. Some of these WIMs are used for data collection to aid strategic planning, pavement design and the quantification of overload claims, while some are used as screening devices in conjunction with Load Control Centers (LCCs) to identify potentially overloaded trucks.

The majority of WIM sensors in South Africa are bending plates (IRD or PAT, both marketed by International Road Dynamics in Canada), while capacitive sensors (Mikros) are used to a lesser extent. Wheel weighers using load cell technology (provided by e.g. Schenk and Klerkscale) are used in some LSWIM applications. Strip sensors (piezo sensors) are widely used as axle counters in South Africa, but not for weighing.

South Africa is a developing country, where government's concern to address numerous social concerns results in inadequate funding of the transport sector. Tolling of strategic national roads is therefore undertaken to ensure that key road infrastructure is well maintained. Contracts with Toll Road Concessionaires stipulate that the extent of overloading on National roads must be monitored and quantified so as to be used to substantiate overload claims against the South African National Roads Agency Limited (SANRAL). The overload claims serve to reimburse the concessionaires for the additional road damage caused by the overloading of trucks, as legislation does not allow concessionaires to prosecute overloading offenders and therefore presents a substantial financial risk to them. There is thus a need for credible and accurate WIM data owing to the large overload claims. Furthermore, SANRAL is under pressure to reduce overloading to limit excessive damage to the general road network and also to limit the amount of money to be paid to Toll Concessionaires.

The most extensive traffic loading data from WIM systems and static weighbridges are thus available from toll roads, more specifically the N1 North, N3, N4 East and Bakwena Platinum toll roads. The data from these projects are scrutinised on a routine basis with the effect that data are generally of good quality and anomalies are researched as they occur.

The bulk of the data used for this study was collected (and is still being collected) from various WIM systems and LCCs on these toll roads. Additional data from special WIM investigations over the past three years were also used. No additional data were collected exclusively for the purposes of this study.

The data streams used for this study are summarised below and discussed in further detail within this chapter.

- Approximately 3 years of weighbridge-linked data (F17 files) from 8 LCCs;
- Between 5 and 12 years of data (RSA files) from 53 WIMs in operation;
- Data from WIM accuracy verifications conducted at almost 30 WIM systems over the past 3 years; and
- 6 months of WIM data from 4 WIMs including the sensor temperature.

3.2 Static Weighbridge Data (F17 files)

At several static weighbridges in South Africa, WIMs are used as screening devices to identify heavily loaded trucks that are subsequently directed to the static weighbridge for accurate weighing. At several of these weighbridges the operating software allows the scalemaster to link the vehicle on the scale with its WIM record on a routine basis using digital images of trucks with the same axle configuration, in backward chronological order. This process will be fully automated at some newer weighbridges (e.g. Bapong, Zebetiela and Donkerhoek) where linking will be done using Automated Number Plate Recognition (ANPR) cameras and software at the WIM and weighbridge. Weighbridge data files, known as F17 files, are extracted from the weighbridge database and contain the full record of WIM and static loads for vehicles that were linked. Data files from weighbridges where linking of vehicles takes place also include the WIM axle unit load and speed of each vehicle.

Data from eight static weighbridges in South Africa where linking of records from WIM screeners is done were used in this research study. The extent of linked F17 data from these systems is summarised below:

Table 3-1: Static Weighbridges with Linked WIM-Weighbridge Records

Static Weighbridge	WIM Screener		Available from
	CTO	Road	
Mid-East LCC	3040	N4 Eb	March 2006
Mid-West LCC	3041	N4 Wb	
Mid-Wit LCC	3042 3043 3044	R555 Eb R575 Nb R555 Wb	
Machado LCC	3045	N4 Wb	
Farrefontein LCC	3046	N4 Eb	
Komati LCC	3047 3048	N4 Eb N4 Wb	
Heidelberg TCC Nb	3058	N3 Nb	September 2006
Heidelberg TCC Sb	3059	N3 Sb	

Many other static weighbridges in South Africa produce data in the F17 format, but do not accommodate the linking of WIM data. They are thus less useful in the research of WIM systems.

3.3 Weigh-in-Motion Data (RSA files)

There are in the order of 100 WIMs installed in National and Provincial roads in South Africa. Data from 53 WIMs on the toll roads to / from Gauteng is analyzed and scrutinized by the author on behalf of the respective concessionaires on a monthly basis, and the quality of data is generally good. The data from these WIMs were available to be used for the purpose of this report and are listed in Table 3-2.

The history and quality of data from other WIM systems (i.e. those not listed in Table 3-2) were not known and they were consequently not considered for the purposes of this research study.

Table 3-2: High-Speed and Screening WIMs

Toll Road Project	CTO	Type	Name	WIM Lanes	Road	Available from
N1 North	3541	HSWIM	Kranskop	2	N1 Nb & Sb	Apr 1997
N1 North	3544	HSWIM	Pietersburg	2	N1 Nb & Sb	Apr 1997
N3	3017	HSWIM	Cedara	2	N3 Nb & Sb	Nov 2000
N3	3021	HSWIM	Hidcote	2	N3 Nb & Sb	Nov 2000
N3	3022	HSWIM	Roosboom	2	N3 Nb & Sb	Nov 2000
N3	3023	HSWIM	Van Reenen	2	N3 Nb & Sb	Nov 2000
N3	3024	HSWIM	Harrismith	2	N3 Nb & Sb	Nov 2000
N3	3025	HSWIM	Wilge	2	N3 Nb & Sb	Dec 2000
N3	3058	Screener	Heidelberg Nb	1	N3 Nb	Jan 2003
N3	3059	Screener	Heidelberg Sb	1	N3 Sb	Jan 2003
N4 East	3040	Screener	Middelburg Eb	1	N4 Eb	Aug 2002
N4 East	3041	Screener	Middleburg Wb	1	N4 Wb	Aug 2002
N4 East	3042 3043 3044	Screener Screener Screener	Mid-Wit Eb Mid-Wit Nb Mid-Wit Wb	1 1 2	R555 Eb R575 Nb R555 Wb	Aug 2002 Aug 2002 Aug 2002
N4 East	3045	Screener	Machado Wb	1	N4 Wb	Sep 2002
N4 East	3046	Screener	Farrefontein Eb	1	N4 Eb	Dec 2002
N4 East	3047 3048	Screener Screener	Komati Eb Komati Wb	1 1	N4 Eb N4 Wb	Aug 2002 Aug 2002
N4 East	3049	HSWIM	Ngodwana Eb	1	N4 Eb	Aug 2002
N4 East	3050	HSWIM	Bronkhorstspruit	2	N4 Eb & Wb	Jul 2005
N4 East	3051	HSWIM	Witbank	2	N12 Eb & Wb	Aug 2002
N4 East	3053	HSWIM	Wonderfontein	2	N4 Eb & Wb	Aug 2002
N4 East	3054	HSWIM	Kaapmuiden	2	N4 Eb & Wb	Aug 2002
Bakwena Platinum	-	HSWIM	Zeerust	2	N4 Eb & Wb	Jan 2003
Bakwena Platinum	-	HSWIM	Bapong	2	N4 Eb & Wb	Jan 2004
Bakwena Platinum	-	HSWIM	Doornpoort	2	N4 Eb & Wb	Jul 2003
Bakwena Platinum	-	HSWIM	Stormvoël	4	N1 Nb & Sb	Oct 2002
Bakwena Platinum	-	HSWIM	Pumulani	2	N1 Nb & Sb	Oct 2002
Bakwena Platinum	-	Screener	Mantsole N1	1	N1 Nb	Aug 2004
Bakwena Platinum	-	Screener	Mantsole N1	1	N1 Sb	Oct 2004
Bakwena Platinum	-	Screener	Mantsole R101	1	R101 Nb	Oct 2004
Bakwena Platinum	-	Screener	Mantsole R101	1	R101 Sb	Oct 2004

Concerns regarding the effect of poor lane discipline on WIM measurements and reported loading information led to the operation of off-scale sensors at the Kranskop WIMs since April 2008 and the Pietersburg WIMs since April 2007 on the N1 North. The off-scale sensors are short piezo-electric sensors of approximately 15 cm each and are installed on the outer edges of the WIMs to identify vehicles that have straddled the WIM sensor and may have been under-weighed as a consequence. If a vehicle triggers the off-scale sensor, the record is still created, but marked in the RSA file as a self diagnosed equipment error. It is thus possible to evaluate the improvement that the implementation of off-scale sensors could have on collected WIM data. Data from these stations were obtained and used for the purpose of this research report.

3.4 WIM Calibration and Verification data

WIM calibrations and accuracy verifications were performed by the service providers of the N1 North, Bakwena and N3 projects over the past three years in accordance with the COST 323 European WIM Specification. A longer history of calibrations / verifications using a two axle test truck was also available for the N1 North. The information from these exercises was used for the purpose of this research study.

3.5 WIM Data with Sensor Temperature

Data files, similar to the RSA format, but that additionally include the WIM temperature for each measurement, were supplied by Mikros Systems for the Kranskop and Pietersburg WIMs from January to June, 2009. This information was specifically used to evaluate a perceived correlation between temperature and WIM error.

4 CHARACTERISING WIM ERROR

4.1 Introduction and Objective

For many years, WIM systems in South Africa were calibrated using a single calibration truck travelling at predetermined speeds. The data from such calibrated WIMs often produced results that appeared to be incorrect. Recent trends in Europe are to use fleets of calibration trucks that are more representative of the total truck population, but even this discrete selection of vehicles may not yield appropriate calibration factors. The experience in South Africa over the last three years is that it is difficult to pass the WIM accuracy verification tests suggested by the European COST 323 WIM Specification owing to differences in errors committed on the respective axles of the vehicle.

This chapter addresses the complexities of WIM error, and aims to determine whether WIM error differs for different types of trucks, different axles on a truck and trucks travelling at different speeds. An understanding of these concepts is important when selecting a WIM calibration procedure and interpreting its results.

4.2 Methodology

The N4 Maputo Corridor hosts six Load Control Centers (LCCs), each operating in conjunction with WIM screeners that are used to identify potentially overloaded trucks. The linked WIM-weighbridge records in the F17 weighbridge data files provided the opportunity to determine the WIM errors for different vehicle types and axle types.

The following methodology was followed:

- Eight different screening WIMs were evaluated. Up to six months of data from their respective LCCs were used for the analysis, depending on the amount of the data per month and the number of WIMs per LCC.
- The calibration factor for each WIM was determined, month by month, for each of the WIMs by comparing the total tonnages by WIM and weighbridge for the linked population of trucks. These factors were applied to WIM data to eliminate the overall miss-calibration of WIMs as best as possible.

- From the calibrated WIM data, the measurement errors were determined for different types of vehicles and different axle units on each type of vehicle. WIM error distributions were then plotted.
- The speed dependence of WIM measurements was evaluated for different axle units and GVM. All trucks used in this analysis travelled at their normal operating speeds.
- For the purpose of this analysis, vehicle records indicating an error on GVM greater than 100% were considered to be erroneous and were hence discarded.

4.3 WIM Error by Trucks Type

The WIM error on GVM was evaluated for four typical truck types. They are 2-axle (1-1 combination) and 3-axle rigid trucks (1-2 combination), 6-axle articulated trucks (1-2-3 combination) and 7-axle interlink trucks (1-2-2-2 combination). In the above descriptions of truck types, the numeric characters indicate the number of axles in consecutive axle units. For example, a 1-2-3 truck is a six-axle truck with a single steering axle, double driving axle and a triple axle combination on the trailer.

The data from eight screening WIMs on the N4 East were analysed, of which four WIMs were selected for the purpose of the report to depict the characteristics of WIM error for typical types of WIM sites:

- Mid-East screening WIM: ***typical*** WIM site (straight, flat road section with trucks travelling at constant speed).
- Mid-West screening WIM: ***uphill*** WIM site (+4 % gradient).
- Farrefontein Eastbound screening WIM: ***downhill*** WIM site (-3 % gradient).
- Machado Westbound screening WIM: "***coasting***" WIM site where little / no acceleration or braking takes place.

The distributions of WIM error on GVM are shown in the graphs below:

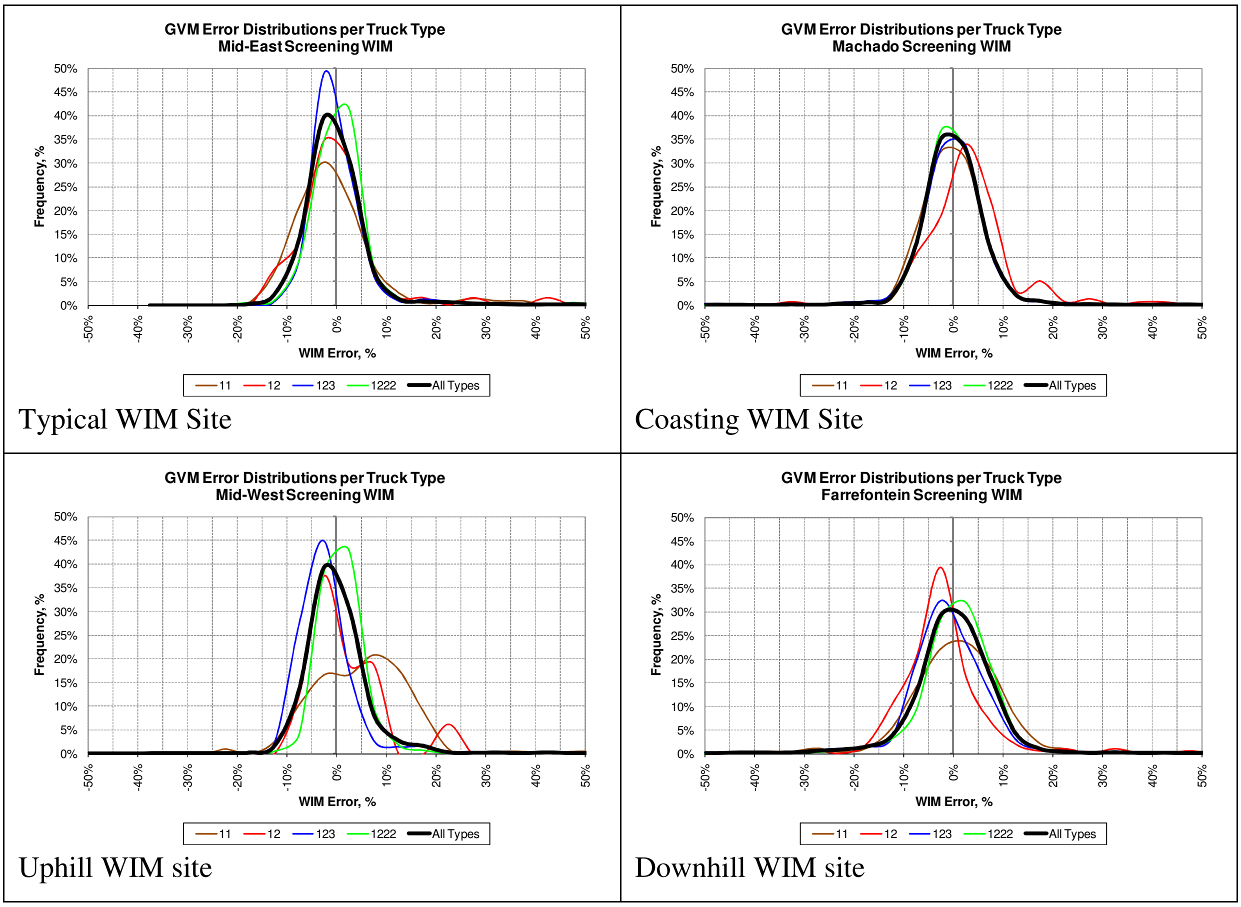


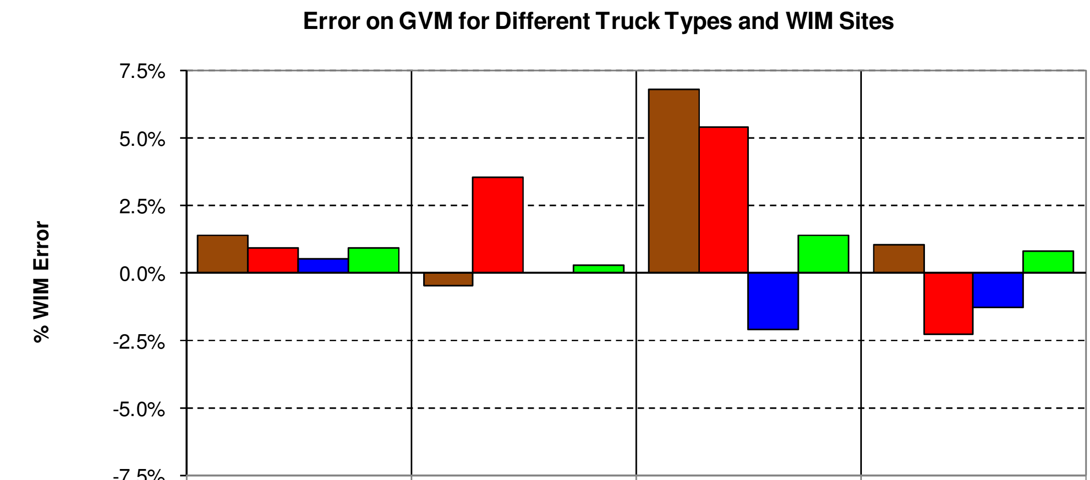
Figure 2: Distributions of WIM Error on Gross Vehicle Mass

A statistical analysis of the WIM error for different truck types at each of the selected four WIMs are summarised below:

Table 4-1: WIM Error on GVM for Different Truck Types

Description	Typical WIM Mid-East Eb	Coasting WIM Machado Wb	Uphill WIM Mid-West Wb	Downhill WIM Farrefontein Eb
	2-Axle Rigid Truck (1-1 Combination)			
Sample Average Error	407 1.4%	376 -0.5%	192 6.8%	750 1.0%
	3-Axle Rigid Truck (1-2 Combination)			
Sample Average Error	66 0.9%	159 3.5%	16 5.4%	208 -2.3%
	6-Axle Articulated Truck (1-2-3 Combination)			
Sample Average Error	998 0.5%	1 650 0.0%	942 -2.1%	1 870 -1.3%
	7-Axle Interlink Truck (1-2-2-2 Combination)			
Sample Average Error	813 0.9%	4 492 0.3%	1 472 1.4%	4 263 0.8%
	ALL COMBINED			
Sample Average Error	2 284 0.8%	6 677 0.2%	2 622 0.6%	7 091 0.2%

The information in the table is also presented in graphic form below:



	Typical	Coasting	Uphill	Downhill
2-ax Rigid	1.4%	-0.5%	6.8%	1.0%
3-ax Rigid	0.9%	3.5%	5.4%	-2.3%
6-ax Articulated	0.5%	0.0%	-2.1%	-1.3%
7-ax Interlink	0.9%	0.3%	1.4%	0.8%

Figure 3: Average WIM Error on Gross Vehicle Mass

From the above it can be seen that the WIM error in Gross Vehicle Mass is not always the same for all types of trucks. The most significant discrepancies were found at the coasting site where 3-axle trucks were over-measured by approximately 3.5%, the uphill site where rigid trucks were over-measured by more than 5%, and the downhill site where the 3-axle trucks were under-measured by approximately 2.5% compared to the average percentage error on all trucks.

It is evident that care should be taken when selecting a calibration truck or fleet of calibration trucks.

4.4 WIM Error by Axle Unit

Considering that the average WIM error on GVM is different for different types of trucks, it is also reasonable to expect different errors on the respective axles of a particular type of truck. The data from the WIMs used in Section 4.3 were re-analysed to determine the WIM error per axle unit for different truck types.

It was found that load is transferred between the respective axle units of a vehicle even when the vehicle is travelling at a constant speed. Normal load transfer is aggravated by upgrades and acceleration, and may even be reversed at WIM sites where deceleration or braking takes place. The transfer of load transpires as aggravated WIM error when dynamic loads are compared to their static counterparts. Whilst these discrepancies in WIM measurements are in fact not true errors and are not caused by poor WIM performance, they are problematic when using axle units for calibration purposes or for WIM accuracy verification, as recommended by COST 323.

The graphs below show the WIM error distributions per axle unit (AU) of 2-axle, 6-axle and 7-axle trucks. For example, axle unit 1 (AU 1) for a type 1-1 truck is the single steering axle and AU 2 is the single driving axle (also refer to description of truck combinations in Section 4.3). The distributions were not plotted for 3-axle data due to inadequate data.

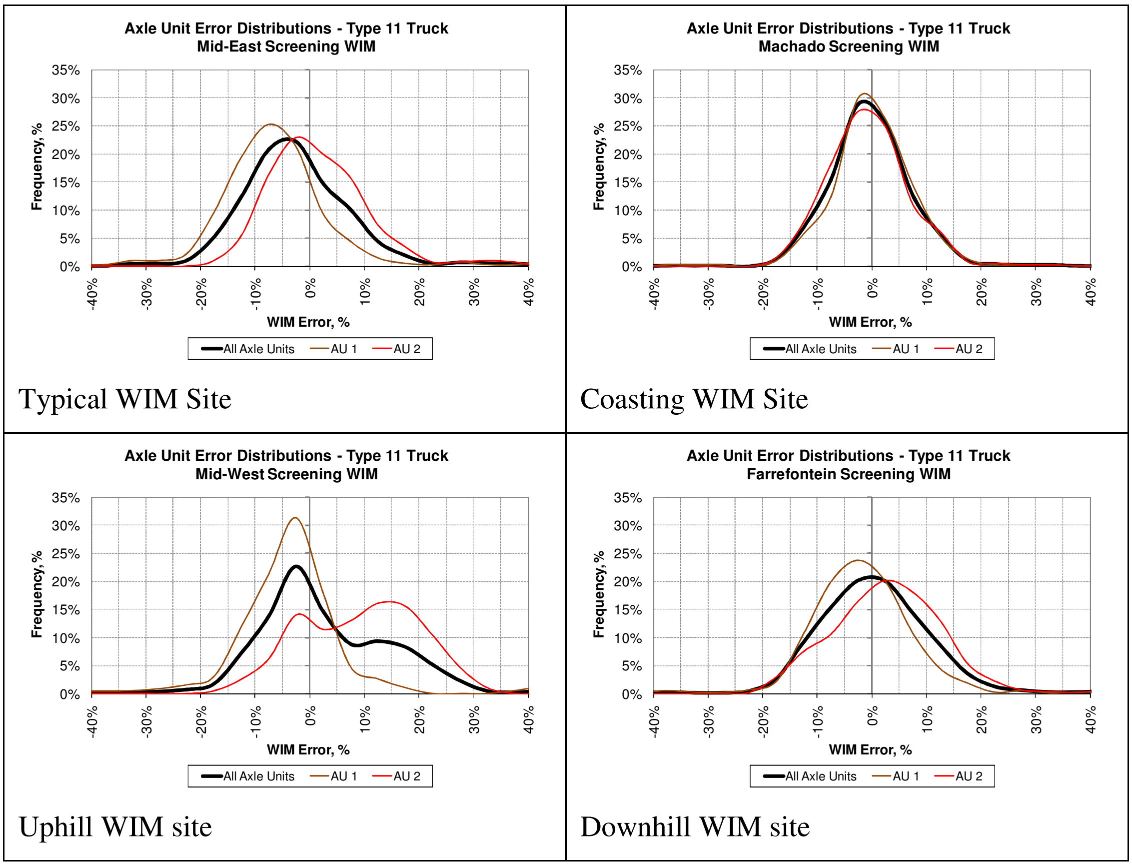


Figure 4: Distributions of WIM Error per Axle Unit, 2-axle Trucks

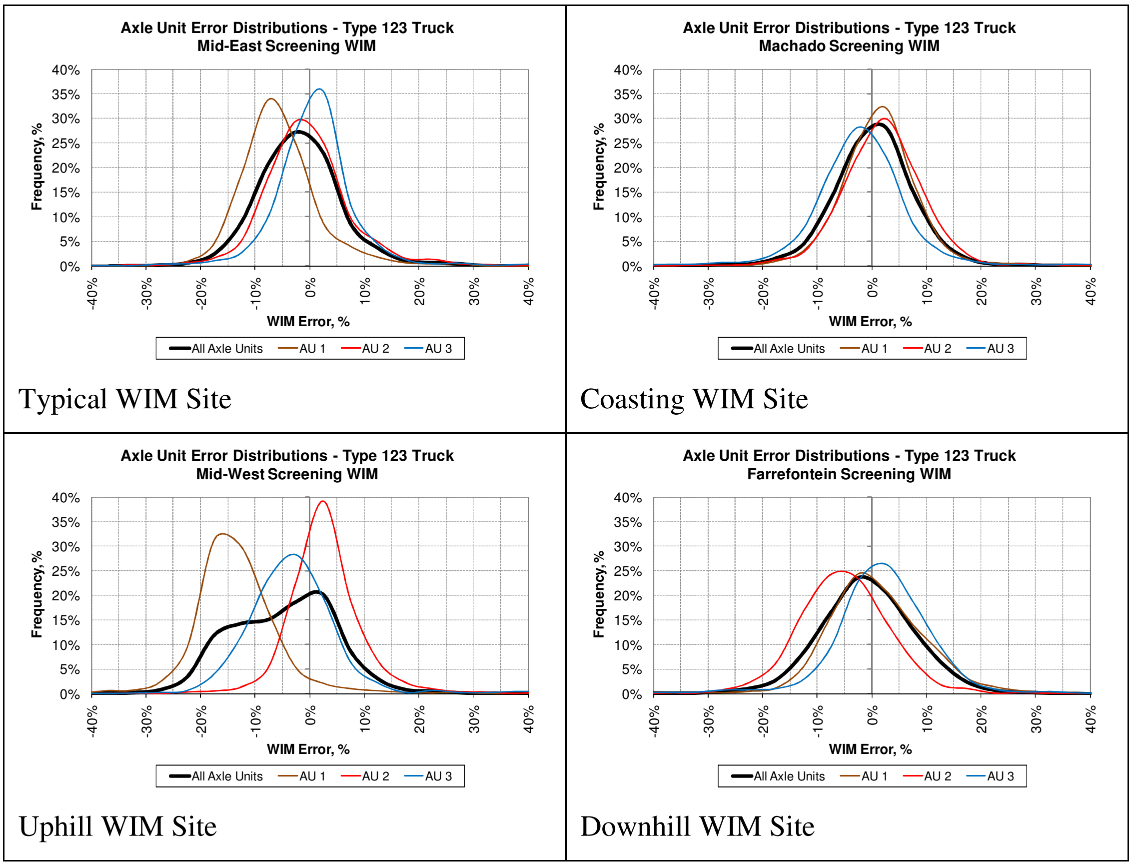


Figure 5: Distributions of WIM Error per Axle Unit, 6-axle Trucks

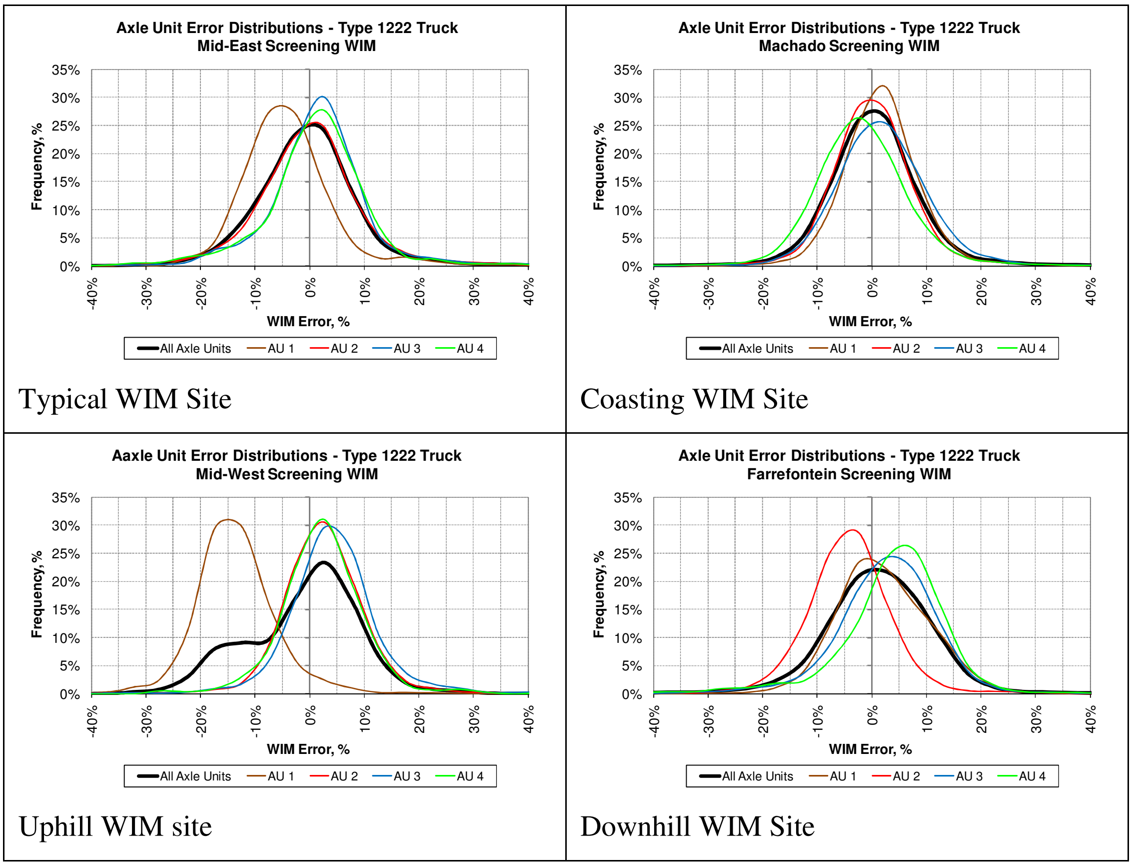


Figure 6: Distributions of WIM Error per Axle Unit, 7-axle Trucks

From the above it can be seen that:

- For the coasting site, the average WIM errors on the respective axle units of a truck are similar. Neither the engine of the truck nor the braking system exerts any forces that cause a transfer of load.
- For the typical WIM site, the truck tractor exerts a horizontal pulling force to maintain a constant speed, and some load transfer occurs. The front axle of rigid as well as articulated trucks at the Mid-East screening WIM are approximately 5% to 6% lighter owing to the rearing action and consequent load transfer away from the front axle.
- For the uphill WIM site, the rearing effect is significantly aggravated. The average front axle loads of all trucks are between 10% and 15% lighter as a result.
- For the downhill WIM site, the rearing action is reversed. The average front axle load of 6- and 7-axle trucks don't show any significant change, but the driving double axles weigh some 4% to 5% lighter as a result of the reversed rearing action. For 2-axle trucks the front axles weigh approximately 4% lighter and the load seems to have been transferred to the single driving axle. It should be noted that this apparent rearing affect is different to what is observed for other truck types and cannot be explained.

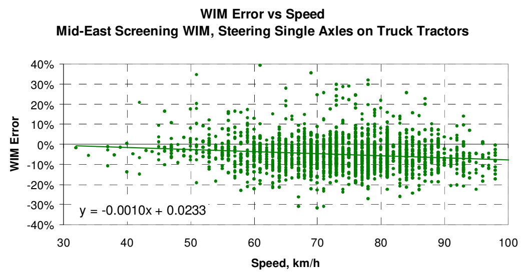
The true dynamic loads of axle units are thus different from their static counterparts owing to the rearing effect. Even for a typical WIM on a straight and flat road section, the front axle weighs in the order of 5% lighter as a result of load transfer.

Care should thus be taken when using axle load loads for WIM calibration or accuracy verification.

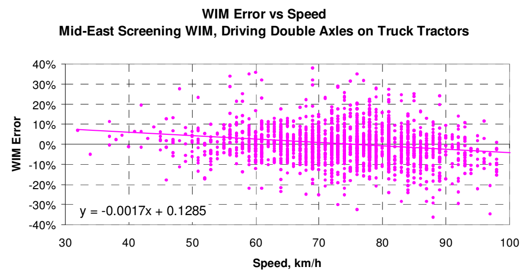
4.5 Speed Dependance

It is commonly believed that WIM measurements are speed dependent. Further investigations were since undertaken to determine whether speed dependence could be confirmed for large populations of axle units or trucks.

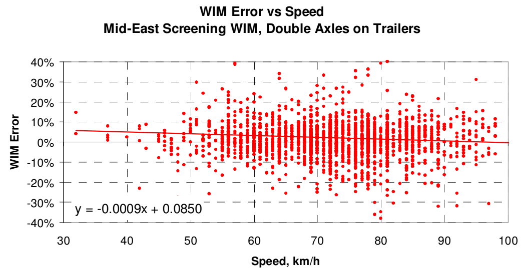
The error in WIM measurements are plotted versus speed in the graphs below. The data from a typical WIM site, the Mid-East screening WIM, was used to develop the graphs. They show error/speed relationships for the axle units where the most significant speed dependence was expected (single steering axles and driving double axle combinations on truck tractors) as well as axle units where speed should have a lesser impact (double and triple axle combinations on trailers of articulated trucks).



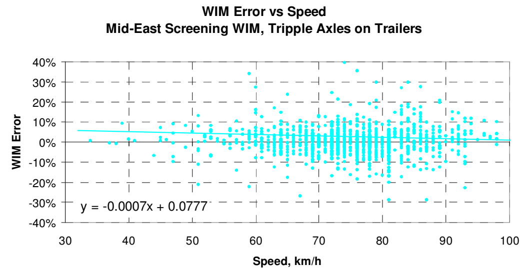
Steering Single Axles on Truck Tractors



Driving Double Axles on Truck Tractors



Double Axle Units on Trailers



Triple Axle Units on Trailers

Figure 7: Speed Dependence of WIM Error, Different Axle Units (Mid-East WIM)

Similar graphs for an uphill site (Middelburg Westbound), downhill site (Farrefontein Eastbound) and a coasting site (Machado Westbound) are attached as Appendix A. The graphs do not indicate a steady pattern of speed dependence. It is also noticeable that the clusters of points are not always symmetrical around the x-axis (particularly the uphill site, Farrefontein).

The graph below shows WIM error versus speed for all axle combinations combined. The plot of WIM errors is more dispersed than for the respective types of axle units, and this may largely be attributed to load transfer.

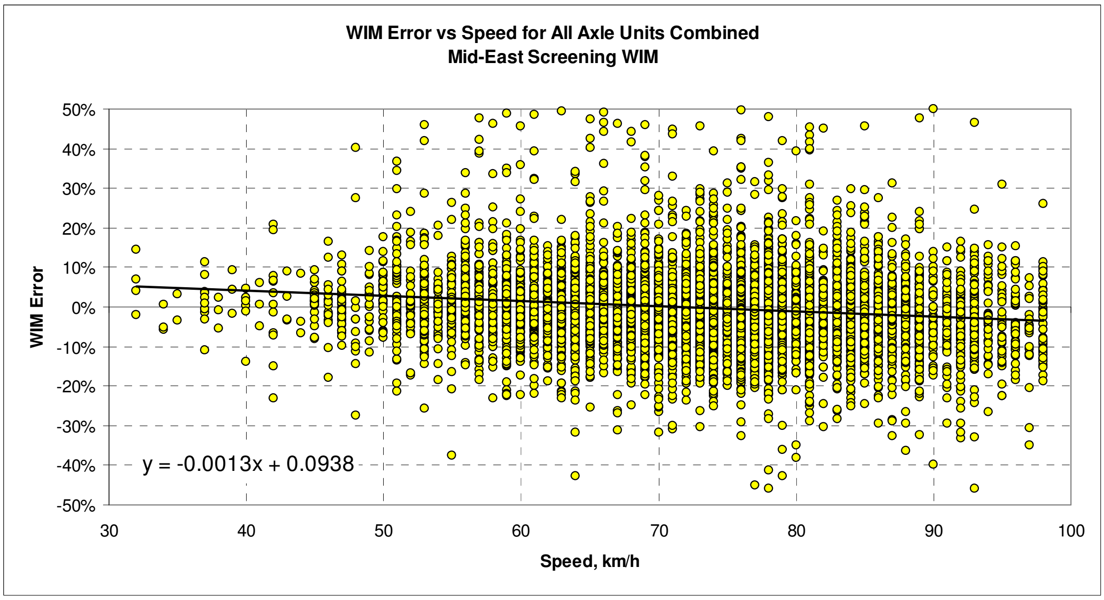


Figure 8: Speed Dependence of WIM Error, All Axle Units Combined (Mid-East WIM)

Considering the effect of load transfer on dynamic axle unit measurements, it is perhaps more appropriate to evaluate the WIM error versus speed relationship based on GVM measurements. The plot below shows the relationship and, after removing outliers (defined here as WIM Error on GVM greater than 2.5 standard deviations from the mean), a linear regression of the data indicated that the average WIM error changes at a rate of approximately -0.09% for every 1 km/h change in speed. The WIM errors in this plot are not as dispersed as for axle units, and have a standard deviation of only 5.3 %.

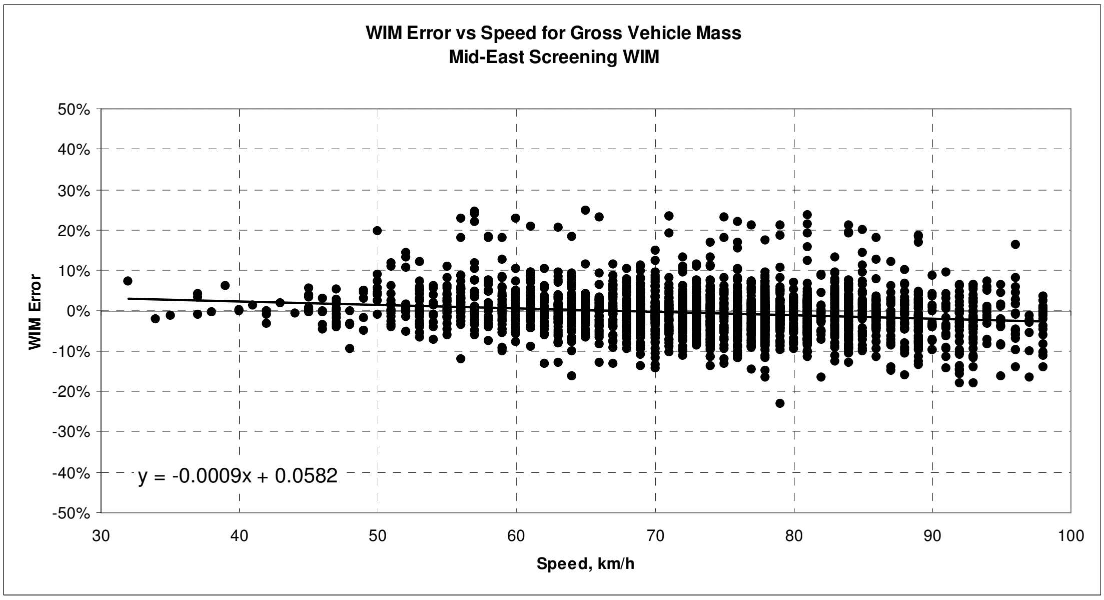


Figure 9: Speed Dependence of WIM Error on GVM at the Mid-East Screening WIM

Based on the results shown above (for a typical WIM) and those in Appendix A (coasting, uphill and downhill WIM sites) it would appear that:

- Whilst speed dependencies are present, it is less severe when considering gross vehicle mass (i.e. when the miss-interpretation of load transfer as WIM error is eliminated).
- Speed appears to play a more prominent role in WIM measurement error at uphill or downhill sites. At the investigated uphill and downhill sites the effect of speed on WIM error was not linear.
- The random nature of WIM error (when considering all vehicles in the traffic stream) makes it almost impossible to predict and apply correction algorithms for it.
- Speed dependence becomes of lesser importance when compared to the wide scatter of WIM errors.

5 RECENT LOCAL EXPERIENCE OF WIM CALIBRATION METHODS

5.1 Calibration Approaches

There are two basic types of calibration methods. The first type (and more frequently applied) uses direct one-to-one correlation of WIM measurements with the actual static axle loads. For this purpose, a single calibration truck, a combination of calibration trucks or a random sample of trucks from the population on the road is used. The other type is calibration using an indirect procedure where a selected loading characteristic from WIM measurements is compared on a large scale to a pre-determined absolute reference.

The difference between the calibration approaches is essentially that the direct methods focus on producing the correct WIM reading for a limited number of vehicle passes for which the static counterparts are known and since accept that all loading results from the WIM will consequently be credible, whereas the indirect methods focus on producing a credible pre-selected loading characteristic by a WIM under normal operating conditions and neglect individual measurement errors to some extent.

The indirect methods use an approach that is similar to automatic self-calibration, originally developed in France (4). Automatic self-calibration is particularly useful for strip sensors (such as piezo or fibre optic cables) that are sensitive to temperature fluctuations and therefore require constant correction (10). In South Africa, bending plates are generally used, for which temperature correction is not deemed necessary and self-calibration is not utilised since it would mask the possible misbehaviour of equipment, pavement deterioration or changes in the traffic pattern. An indirect post-calibration method as part of the quality control of WIM data (as already used internationally (3)) is preferable.

5.2 Success of WIM Calibration Methods

5.2.1 Calibration Methods using Test Trucks or Random Sample

In South Africa, three one-to-one correlation methods have been used for WIM calibration in the recent past. They use a 2-axle truck, a 3-axle truck and a randomly selected sample of trucks from the road. No other direct calibration methods, e.g. calibration fleets or instrumented trucks, have been used.

a) Two-axle Calibration Truck

One-to-one calibration was done for many years using a 2-axle sand truck. These trucks are readily available, relatively cheap and simple to load. On the N1 Toll Road Project, the calibration truck was used to make at least 50 passes over the WIM sensor at a speed of approximately 60 km/h. The calibration factor was determined using the total mass as reference. The differences in measurement errors on the front and rear axle respectively were noted, but not used in the calibration process. Variations in speed were introduced on an ad-hoc basis. Speed dependence was noted and served as an indication of the quality of the WIM installation, but was not used in calibration calculations.

b) Three-axle Calibration Truck

In 2006 SANRAL adopted the COST 323 European WIM Specification (2) and used it as a basis for their Standard Specification for Traffic Data Collection (13). The use of a single 3-axle truck was specified for WIM accuracy verification exercises because it provides data for all four accuracy test elements (single axles, axle groups, axles within a group and GVM). These trucks are readily available, relatively cheap and are easier and safer than articulated trucks to turn around on a highway to make several passes over the WIM. Tests were carried out under full repeatability (Type r1) and environmental repeatability (Type I) conditions as described by COST 323.

The majority of WIMs on the N1, N3 and Bakwena Toll Roads in South Africa failed the specified Class C(15) accuracy during verification tests in 2007. Poor calibration contributed to these failures. The “passing potential” of WIMs was thus evaluated by suppressing the systematic error as determined from the verifications – the average of the percentage errors based on each of the four accuracy test elements were used to determine a calibration factor, that was then applied to the already recorded WIM measurements used for the accuracy verification. The re-evaluation of the post-calibrated WIM data showed that, even without systematic error, approximately half of them would still fail the COST 323 verification owing to different average errors for different axles on the vehicle and the excessive spread of errors per axle. The accuracy verification results for the twelve WIM systems on the N3 Toll Road from May 2007 are shown in Appendix B as an example.

In general, a fast moving 3-axle vehicle rears up and causes lifting of the steering axle while the second axle tends to push down harder than the third axle, yet totally different reactions were observed at many WIMs. The WIM is thus already at a disadvantage given the (true) variation in reference masses of axles. Most WIMs consequently failed the verification tests based on the evaluation of single axles (i.e. front axle) and axles within a group. Measurements were also found to be speed dependent at many of the WIMs.

The graphs below show, as an example, the WIM errors from the accuracy verification of the Hidcote Southbound WIM in October 2006 using a 3-axle sand truck. The extent and speed dependence of the WIM errors can be clearly seen, even though the particular WIM passed accuracy Class C(15).

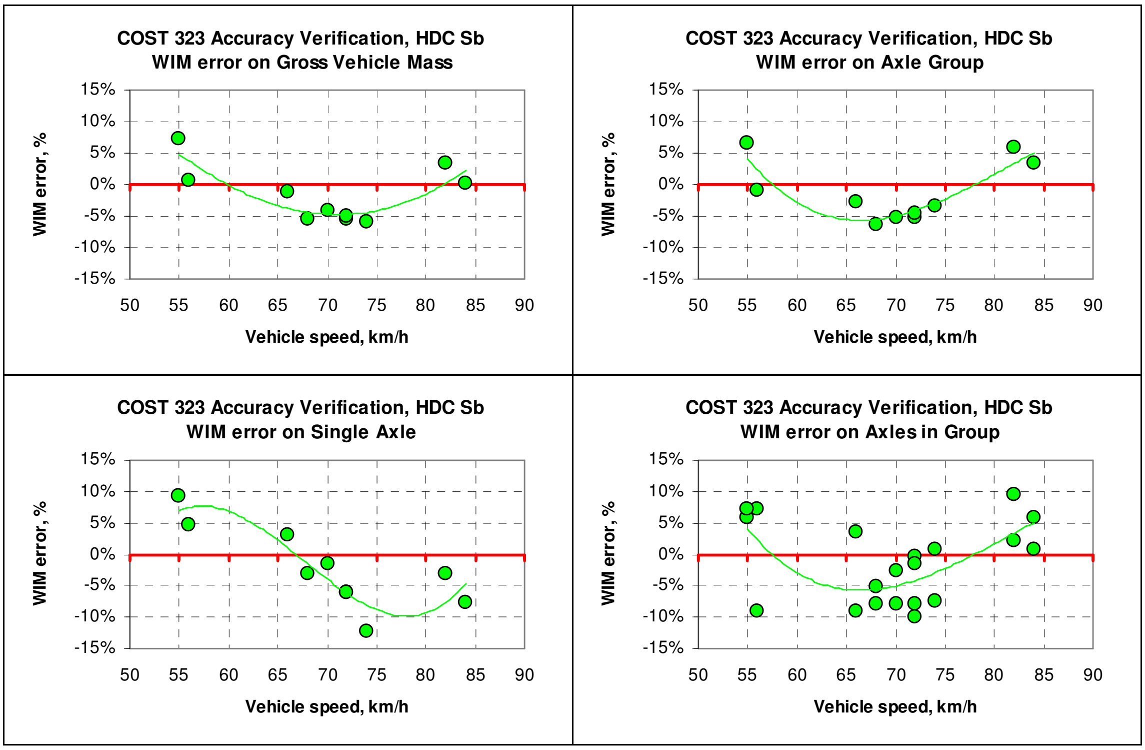


Table 5-1: WIM Errors from the Hidcote Sb Accuracy Verification, Oct 2006

Whilst the WIM errors for one specific vehicle with one load case often follow a speed dependent pattern, it should be noted that these patterns are different for the various vehicles in the traffic stream. When WIM errors for all vehicles are combined, the result is a random scatter (see Section 4.5) that is almost impossible to suppress using speed-specific correction algorithms.

c) Random Sample of Trucks

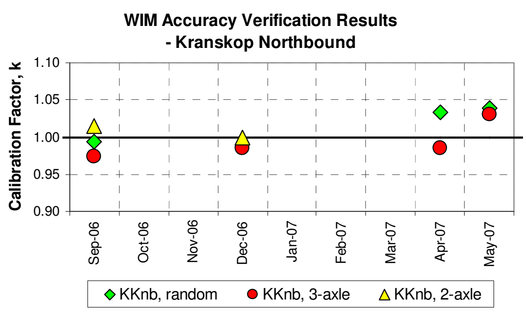
Random sample calibrations are done in South Africa, but on a much smaller scale than single vehicle calibrations. At least 30 trucks are randomly selected from the road, and once they have passed over the WIM at operating speed they are pulled off the road for static weighing. It conforms to the full reproducibility (Type R2) and environmental repeatability (Type I) test conditions described by COST 323. This method has only been introduced on one toll road (N1 Toll Road) for routine use on a 6-monthly basis. It proved to be a more reliable test than the 3-axle truck, and WIMs in known good condition achieved the required COST 323 class C(15) accuracy.

Whilst the random sample calibration results are perceived to be more reliable than using single calibration vehicles, the downside of using this method is that it is costly, time consuming and may require special arrangements for static weighing.

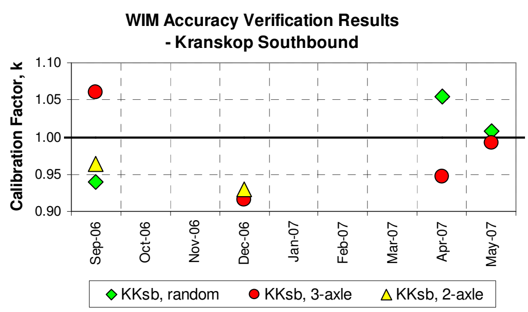
d) Comparison of Results from 2-axle, 3-axle and Random Sample Calibrations

The random sample and 3-axle truck methods were used in combination for verification of WIM accuracy on the N1 Toll Road in South Africa up to 2008. Until 2007 the 2-axle truck was also used to compare its results with those from the random and 3-axle truck calibrations because a long history of 2-axle truck calibration results was available. It was found that the three direct methods did not corroborate each other well, and the loading characteristics from WIMs calibrated with the random sample method were not always credible. It must be noted that the reference masses for the random sample of trucks on this project are obtained using mobile low-speed WIMs, and the sometimes unrealistic loading results from such calibrated WIMs casts doubt on the appropriateness of this practice.

An example of the performance of the three direct methods at two WIMs on the N1 Toll Road is shown in Figure 10 below. Both these WIMs were well constructed in a good pavement, such that accuracy class C(15), as described in the COST 323 guideline, should have been comfortably achieved. No alterations to the WIM installations or calibration settings were made during the analysis period (September 2006 to May 2007), and all calibration factors from all methods should ideally have been the same.



Kranskop Northbound



Kranskop Southbound

Figure 10: Direct Calibration Results at Kranskop WIM

It is evident from the results shown above that calibration factors from the three direct methods were sometimes very different, and the calibration factors from individual methods were not sufficiently repeatable either. The results shown above corroborate the general perception, based on years of experience in WIM calibration, that direct calibration methods are not adequately reliable.

5.2.2 Weighbridge-Linked Method

The F17 data can be used to determine the systematic error of a WIM system in a similar manner as the Random Sample calibration. It must be noted that the selection of trucks at LCCs is aimed at heavily loaded trucks and is therefore not random. Nonetheless, two important qualifications make it superior to any other calibration method:

- The sample of trucks is extremely large; hundreds or even thousands of vehicles are typically available on a monthly basis to determine calibration factors for WIMs.
- The static reference masses of vehicles are determined accurately on a well calibrated static scale.

It is important to note that the South African legislation for prosecution of overloaded heavy vehicles does not include loading limits for axles within a group, and static scales are designed to determine the static masses for axle groups only.

The downside of the Weighbridge-Linked Method is that it can only be used for screening WIMs, and requires continuous linking of WIM records with their counterparts in a specially designed weighbridge database. It therefore cannot serve the purpose of general WIM calibration, but is exceptionally valuable for research purposes.

5.2.3 FFF Method – Indirect Calibration using Front Axle Tracking

An indirect calibration method, named the FFF Method, was used from approximately 2007 up to the beginning of 2009 for data collected on two Toll Concessions, viz. the N3 and Bakwena Platinum Toll Roads. The method emanated from a WIM data validation criterion introduced by SANRAL in 2007, whereby they only accepted WIM data of which the average front axle mass (called FFF) of a particular population of articulated trucks was between 5.9 t and 6.4 t (15). The trucks in this population all had seven or more axles in total, a single steering axle weighing between 2.5 t and 10 t and a double driving axle on the truck-tractor of between 14 t and 20 t. The monitoring of front axle loads of certain trucks is already used internationally as a part of WIM data quality control (3).

The average front axle mass of these trucks is remarkably stable since the kingpin of the first trailer transfers its load almost directly onto the centre of the double driving axle, and only about 7% of the load on the first trailer is transferred onto the front axle. The front axle primarily carries the engine of the truck, of which the mass does not vary substantially for these truck-tractors.

However, the horizontal pulling force applied at the kingpin causes rearing (lifting of the front axle) of the truck-tractor and hence a reduction in front axle mass. Even on a flat road at a constant speed the rolling resistance on the trailer axles needs to be overcome and the pulling action on the truck-tractor still causes rearing that reduces the average front axle mass of a loaded truck by approximately 5% (see Section 4.4). The extent of rearing is different for every WIM, and is primarily affected by gradient, acceleration and braking. The rearing effect may even be reversed at downhill WIM sites. SANRAL's acceptance range allowed for some of the variability of front axle masses for different WIMs.

SANRAL never intended that their data validation criterion be used as a calibration method. However, the acceptance of WIM data is important to toll road operators whose concession agreements allow them to claim back from SANRAL the cost of the additional pavement damage due to overloading. Data was therefore calibrated (assuming that SANRAL's range of front axle masses for validation purposes could be used for this purpose) to produce an acceptable average front axle mass for the particular selection of trucks.

The FFF Method is suitable for typical WIM sites with negligible gradient and no acceleration or braking. For other WIMs the true FFF value may vary substantially. This was proven by evaluating the FFF for eight screening WIMs that were well calibrated using the

Weighbridge-Linked Method (see Section 5.2.2). The analysis showed that only half of the WIMs passed the front axle data validation criterion, as illustrated in Figure 11 below.

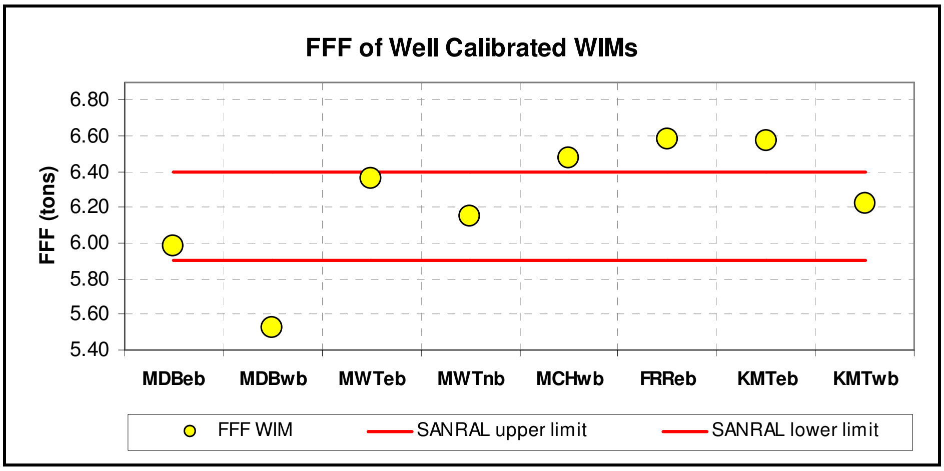


Figure 11: FFF of WIMs Calibrated with the Weighbridge-Linked Method

It should be noted that the screening WIMs mentioned include one uphill site (MDBwb) and one downhill site (FRReb) – the FFFs from these two WIMs may be regarded as extremes.

6 DEVELOPMENT OF A NEW WIM CALIBRATION METHOD

6.1 Criteria for New Calibration Method

It is accepted that the Weighbridge-Linked Method is the best calibration method available, but it can only be applied on a routine basis at screening WIMs where linked F17 files are available. This practice is widely applied internationally for WIMs in the vicinity of weighbridges that are used for law enforcement [(3)]. An alternative method is required for WIMs where the Weighbridge-Linked Method cannot be applied. Some requirements were set for the method based on international practices and local experience:

- The method should not make use of test trucks. 2-axle and 3-axle test trucks yielded dubious results in the past, and the use of articulated test trucks is not safe and practical at all WIM sites.
- The method should not make use of a random sample of trucks from the traffic stream, because it cannot be used at all WIMs for safety and geometric reasons and it is often difficult to determine accurate static reference loads in practice.
- The method must be simple. The use of, for example, different calibration factors for different axle units or truck types travelling at different speeds is too complicated for routine use.
- The method must be robust. In practice, some WIMs are also installed on less appropriate road sections such as uphill or downhill sections or where some acceleration or braking takes place. A single method is required to calibrate various types of WIM sites.
- The method should allow for calibration of WIM data in retrospect in order to make optimal use of historic data that may have been miss-calibrated, but otherwise stable.
- The method must be accurate. It must be able to estimate the most appropriate calibration factor that can be applied to the total truck population to suppress systematic error accurate to within, say, 3%.
- The method should incorporate data quality checks that can be used to validate the appropriateness of the calibration result and acceptability of loading data.

6.2 Development History

The development of the new calibration process took place primarily over the past two to three years. The concept was initially known as the FTR Method. Further refinements were made in 2008 as part of the revision of the South African Mechanistic Pavement Design Method [(14)] and the calibration method is now known as the TT Method (Truck Tractor Method).

The development of the FTR method emanated from the FFF method (see Section 5.2.3), but aimed to account for the effect of rearing. During 2007 the author investigated several methods to predict the average front axle load at any particular WIM with consideration of the rearing effect. One such method was proven to be adequately viable for further evaluation, and it became known as the FTR (Front-axle Truck-tractor Ratio) Method.

The FTR is the ratio between the front axle mass, F, and the total truck tractor mass, T, of articulated 6- and 7-axle trucks with a single steering and double driving axle. The use of 6- and 7-axle trucks provided a large population of reference trucks and, unlike the FFF Method, (see Section 5.2.3) that used only 7-axle trucks, the FTR Method could also be used on routes where 7-axle trucks are not abundant. The formula for the calculation of FTR is given below.

$$FTR = \frac{F}{T} \quad (1)$$

After plotting the FTR against gross vehicle mass for various WIMs the author discovered that the FTR for loaded trucks (typically the higher third of the GVM range) was stable, albeit at different levels for respective WIMs. It therefore showed potential to be used as an indicator of the extent of truck tractor rearing at a particular WIM site. The higher 30 % of the GVM range was selected as the norm the to identify the maximum stable part of the graph after inspecting the FTR plots from a variety of WIMs in different operating conditions. The FTR for WIM sites with significant rearing were lower than at WIMs where rearing is less prominent.

The FTR method was incorporated into existing data analysis software by Dr Slavik of BKS (Pty) Ltd consulting engineers to aid further research. Figure 12 shows a plot of FTR versus gross combination mass for a typical WIM. The banana-shaped plotted mass gave rise to the nickname for the analysis software: Banana. The graph was used to identify the total GVM range (excluding outliers) for the particular WIM, from which the higher 30% ‘window’ was determined and used for further calculations. The FTR is a dimensionless ratio and therefore the vertical level of the banana cluster is not influenced by WIM calibration; it shrinks proportionally to the left for under-calibrated WIMs and stretches to the right for over-calibrated WIMs. Provided that the GVM range is redefined for every new set of WIM data, the window stretches with the banana and the trucks included in further calculation are therefore not influenced by poor WIM calibration. The average front axle mass, F30, and average FTR, FTR30, are calculated from trucks falling within the higher 30 % window.

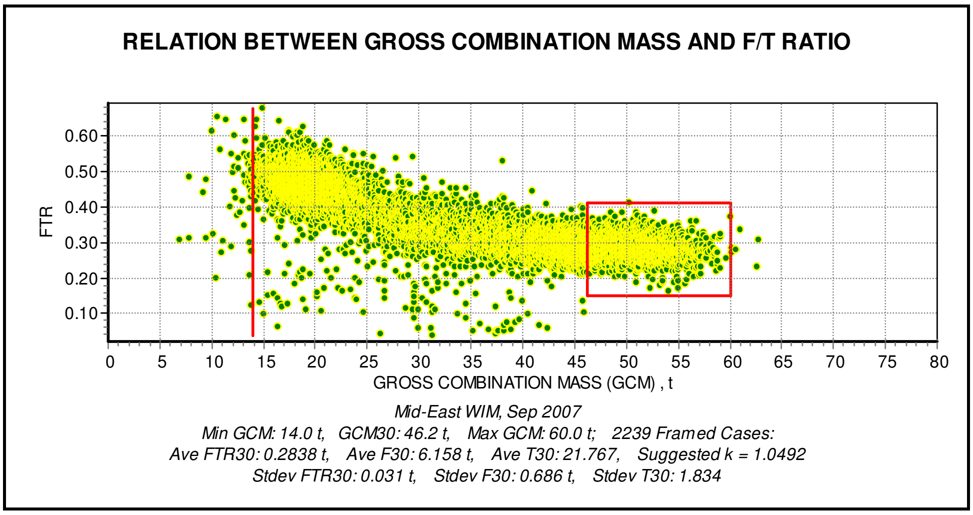


Figure 12: Plot of FTR vs Gross Vehicle Mass

It was found from the analysis of well calibrated WIMs that there is a stable relationship between F30 and FTR30. Fifteen month's data (October 2006 to December 2007) from eight screening WIMs were calibrated month by month using the Weighbridge-Linked Method, and then analysed to determine monthly values of F30 and FTR30. The data were used to perform a regression analysis to describe the relationship mathematically. The regression analysis graph is shown in Figure 13.

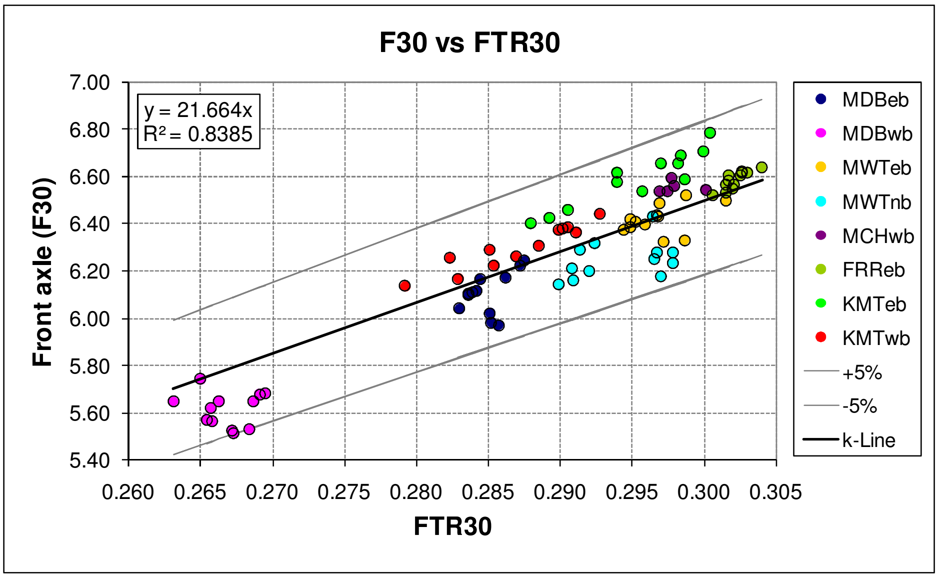


Figure 13: Relationship between F30 and FTR30

The relationship between FTR30 and F30 for a well calibrated WIM is given in Equation (2) below. All average front axle loads (F30) from the wide variety of WIMs were within 5% of the regression line, and the majority were within 3%.

$$F30_{calibrated} = (FTR30)\cdot(21.7) \tag{2}$$

As mentioned, FTR30 is a dimensionless ratio and it is therefore not influenced by miss-calibration. Once the FTR30 and $F30_{raw}$ for a particular set of un-calibrated WIM data has been determined, the regression equation can be used to calculate $F30_{target}$ using Equation (3) below.

$$F30_{target} = (FTR30)\cdot(21.7) \tag{3}$$

The calibration factor k_{FTR} required to produce the $F30_{target}$ is shown in Equation (4).

$$k_{FTR} = \frac{F30_{target}}{F30_{raw}} \tag{4}$$

Initially the application of the FTR Method entailed the visual identification of the GVM range using the banana cluster. The level of the FTR inside the 30% window was adequately stable to make the method reasonably insensitive towards the identification of different GVM ranges by different operators, yet this brought an undesirable human subjectivity into the calibration process. The Banana software was consequently adjusted such that the selection of the 30% window was automated.

An iterative feature (proposed by Slavik) was built into the Banana software whereby the k-factor determined from Equations (3) and (4) was applied to the WIM data repeatedly until Equation (2) was satisfied for a fixed predetermined GVM range of 14 t to 60 t. The predetermined GVM range was based on the Banana graphs from the well calibrated WIM systems that were used in the development of the FTR Method. The iterative process drives the banana cluster into the window instead of setting the window according to the position of the banana. The procedure almost always concluded within ten iterations, and totally eliminated the need for human intervention in the selection of the 30% window. After several hundreds of analyses using the Banana software, not a single case was recorded when the iterative process did not converge to a solution.

The accuracy of the FTR Method was tested using screening WIM data from September 2006 to May 2007. The performance of the method was tested in terms of its ability to reproduce k-factors of 1.0 for data that was calibrated month by month using the Weighbridge-Linked method. The WIMs used for the evaluation incorporated differences in road geometry, truck traffic composition and extent of loading, and provided a thorough test of the robustness of the FTR method. The discrepancies in k-factors are summarised below.

Table 6-1: Accuracy of the FTR Calibration Method

WIM	Site Description	Error in k-factor
3040 – Mid-East	Typical National Freeway	-0.1 %
3041 – Mid-West	Uphill (4%) National Freeway	1.3 %
3042 – Mid-Wit eastbound	Major Provincial Arterial	-0.6 %
3043 – Mid-Wit northbound	Regional Road, lightly trafficked	1.8 %
3045 – Machado	Typical National Highway	-1.3 %
3046 – Farrefontein	Downhill (3%) National Highway	-0.7 %
3047 – Komati eastbound	National Road with speed reduction	-3.3 %
3048 – Komati westbound	Medium speed screening lane	-1.2 %
Average Discrepancy		***-0.5 %***
Standard Deviation of Discrepancies		***1.6 %***

It can be seen from the above that the FTR Method corroborated the weighbridge-linked method well for a variety of vastly different WIMs, with an average discrepancy of -0.5 % and a standard deviation of a mere 1.6 %.

It should be noted that, once the iterative process of the FTR Method is concluded, the calibrated front axle load, F30, is equal to FTR30 multiplied by the calibration constant of 21.7 – see Equation 2. When FTR is expressed in terms of F30 and the truck tractor load of Selected Trucks, T30, the relationship can also be rewritten (see Equation (1)) as follows:

$$F30_{calibrated} = \frac{F30_{calibrated}}{T30_{calibrated}} \cdot (21.7) \qquad (5)$$

After simplification of the equation, it simply yields $T30_{calibrated} = 21.7$. The FTR Method drives the truck tractor load to 21.7 t, which is also the calibration constant.

In May 2008, the author presented a paper (co-authored by Dr MM Slavik) called "Macroscopic WIM Calibration" at the 5th International Conference on WIM in Paris (14). The paper discussed various options for WIM calibration including the Weighbridge-Linked Method, the FFF Method and the FTR Method. The FTR Method was recommended as the most appropriate post-calibration technique for WIM systems where linked weighbridge data are not available. The paper and presentation was particularly well received by the international audience, and was honoured as the best presentation on WIM.

6.3 The Truck Tractor (TT) Method

6.3.1 Introduction

In August 2008, BKS (Pty) Ltd offered the FTR Method to SANRAL to be considered as a post-calibration method for WIM data. The development of the Truck-Tractor (TT) Calibration Method was the direct outflow of a formal review and refinement of the FTR Method for SANRAL (14).

Whilst the FTR Method determined a target front axle load to make it directly comparable to the FFF Method, the TT Method simply calibrates for the truck-tractor load. The target truck-tractor load used in the TT Method is the same as the calibration constant of the FTR Method – these two methods are directly related. The end result of both methods is a predefined sub-population of 6- and 7-axle trucks having the desired average truck tractor mass.

One prominent improvement in the TT Method that emanated from the review of the FTR Method was that the average axle load is now used instead of Gross Vehicle Mass (GVM) as selection criteria for identification of the calibration sub-population of trucks. This improvement proved to have an insignificant impact on the calibration constant, but it is intuitively accepted that 6- and 7-axle trucks are better represented when the average axle load is used and the method should be more stable.

Although the TT Method is almost identical to the FTR Method, it was fully redeveloped (using the same basic methodology as for the FTR Method) using data other than what was used for the development of the FTR Method. The development process included the following steps:

- The Weighbridge-Linked Method was used to determine accurate calibration factors for available screening WIMs.
- A database of well calibrated WIM data was produced by applying the factors obtained from the Weighbridge-Linked Method.
- The selection criteria of trucks to be used in the calibration method (called Selected Trucks) were refined.
- The truck tractor loads of Selected Trucks from a variety of WIM systems were calculated.
- The accuracy of the calibration method was tested against the Weighbridge-Linked Method to determine how the combination of the criteria to identify Selected Trucks, the target truck tractor mass and the iterative calibration procedure performs in practice.

6.3.2 Truck Tractor Calibration Constants

The reference database of well calibrated WIM data was established from screening WIM and weighbridge data for the period October 2006 to December 2007. Certain months of data were discarded owing to known WIM failures, unsuitable pavement or inadequate data. The WIMs and weighbridges that were used for the development of the TT Method are listed below:

Table 6-2: WIMs and Weighbridges with Linked F17 Data

WIM Data			Weighbridge Data	Road
CTO No	Abbreviation	Name		
3040	MDBeb	Middelburg Eb	Mid-East LCC	N4
3041	MDBwb	Middelburg Wb	Mid-West LCC	N4
3042	MWTeb	Mid-Wit Eb	Mid-Wit LCC	R555
3043	MWTnb	Mid-Wit Nb	Mid-Wit LCC	R575
3045	MCHwb	Machado Wb	Machado LCC	N4
3046	FRReb	Farrefontein Eb	Farrefontein LCC	N4
3047	KMTeb	Komati Eb	Komati LCC	N4
3048	KMTwb	Komati Wb	Komati LCC	N4
3058	HDBnb	Heidelberg Nb	Heidelberg TCC Nb	N3
3059	HDBsb	Heidelberg Sb	Heidelberg TCC Sb	N3

The Weighbridge-Linked Method was used to calibrate the screening WIM data. The linked F17 files from the static weighbridges were analysed, month by month, to determine the systematic error committed by their respective screening WIMs and the appropriate factors, k_{WL}, to suppress the systematic error. The k_{WL} factors were then applied to all axle loads in the RSA files obtained from respective WIMs. These RSA files were thus exceptionally well calibrated.

It was confirmed, using the calibrated data, that the distribution of errors on GVM committed by a WIM in a reasonably good operating environment has a standard deviation, s_e, in the order of 5% to 8%. A standard deviation greater than 10% would point to an unacceptably large random error component (see further discussion in Section 7.3). Typically, less than 2% of WIM errors fell outside of the ± 50 % range and were considered to be outliers – such records were discarded for the purpose of determining WIM systematic error because they could have been caused by clipping of the sensor or linking of incorrect vehicles in the F17 database. An example of a typical distribution of WIM error on GVM, after applying the k_{WL} calibration factor, is shown in Figure 14. The error distribution is almost perfectly centred on zero with a standard deviation of 6.6 %. The Mossie software [20] was used to analyse the weighbridge data and produce the output shown in the figure.

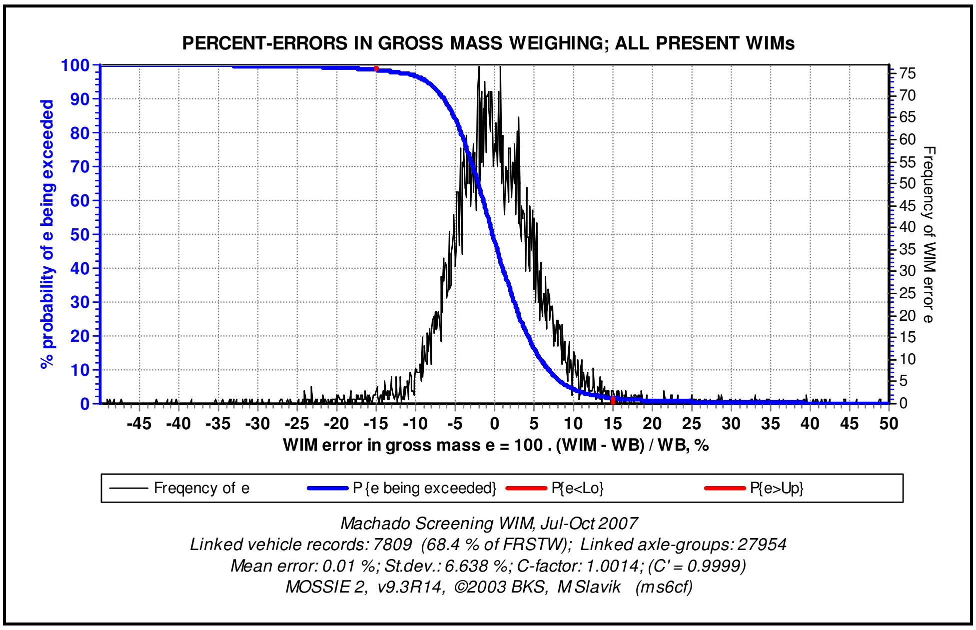


Figure 14: WIM Error Distribution on GVM, Machado WIM

The Heidelberg southbound data showed standard deviations of WIM error on GVM greater than 10%. This was caused by rapid pavement deterioration. Furthermore, the Heidelberg northbound screener's error distributions were not symmetrical, resulting in unrealistic k_{F17} factors. The Heidelberg data were therefore not considered fit for this purpose.

The numbers of linked records in a month for the respective WIM screeners were often in the thousands. However, for some stations (e.g. Mid-Wit northbound), there were sometimes less than 200 linked records in a month. Months when the number of linked records were below 100 vehicles were not used (or combined with other months to increase the sample size), and those with 100 to 200 linked records were used with caution.

The Weighbridge-Linked calibration factor, k_{WL}, was determined using the formulae:

$$k_{WL} = \frac{1}{1+e} \quad (6)$$

$$e = \frac{\sum \left(\frac{D_i}{S_i} - 1 \right)}{N} \quad (7)$$

With: $-0.5 < e_i < 0.5$

$N > 100$, but preferably > 200

Where:

k_{WL}	Adjustment factor using Weighbridge-Linked Method
e	Percentage systematic WIM error
e_i	Percentage WIM error on GVM of truck i
D_i	Dynamic GVM of truck i, from WIM
S_i	Static GVM of truck i, from weighbridge
N	Number of linked F17 records with $-0.5 < e_i < 0.5$

The standard deviation of WIM error, s_e, is calculated a follows:

$$s_e = \sqrt{\frac{\sum (e_i - e)^2}{N - 1}} \tag{8}$$

Loading forms part of the selection criteria for suitably linked F17 records. Records with WIM error on GVM exceeding 50% were discarded, and therefore it was required to use an iterative process to find k_{WL}.

Step 1:	Calculate first estimate of $k_{WL,}$ using $k_{WL} = 1 / (1 + e)$
Step 2:	Apply k_{F17} to raw data set
Step 3:	Calculate adjustment for residual systematic error, $k_{adj} = 1 / (1 + e)$
Step 4:	Refine k_{WL} by multiplying with k_{adj}
Step 5:	Repeat steps 2-4 until Step 2 yields $k_{adj} = 1.000$

The monthly calibration factors for each WIM were applied to the axle loads in the RSA files using the following formula:

$$D_{Ai} = k_{WL} \cdot D_{Ri} \tag{9}$$

Where:

D_{Ai}	Adjusted Dynamic load of axle i
D_{Ri}	Raw Dynamic load of axle i
k_{WL}	Calibration factor from Weighbridge-Linked Method

Three sets of filters were used to select the trucks to be used in the Truck-Tractor Method:

1) Formal correctness of individual lines of data;
2) Conformance to axle spacing criteria; and
3) Conformance to loading criterion.

The formal correctness of WIM data was checked by confirming that the lines of data in the RSA file conform to the National Standard [16] and also by checking for logical errors such as backtracking of date and time, heavy vehicles with zero or one axle, three or more steering axles etc. These are standard data quality checks used in routine analysis of WIM data, and are not specific to the TT Method.

The axle spacing criteria emanated from the SANRAL data validation guidelines and were also used in the FTR Method. They were developed using typical distributions of axle spacing for articulated trucks and their aim is to filter out a steady sub-population of 6- and 7-axle articulated trucks with a single steering and double driving axles on the truck tractor. The criteria are as follows:

- Heavy vehicle with 6 or 7 axles in total
- Axle spacing of 2.9 m – 3.9 m between 1st and 2nd axle
- Axle spacing of 1.2 m – 2.4 m between 2nd and 3rd axle
- Axle spacing of 4.5 m – 9.0 m between 3rd and 4th axle

Eligible Trucks are defined here as 6- and 7-axle trucks conforming to the above axle spacing criteria.

The average axle load for Eligible Trucks typically ranges between 2.0 t and 8.5 t. It was confirmed from more than 100 analyses that, for vehicles with an average axle load of 6.5 t – 8.5 t, the average truck-tractor loads at various WIMs were approximately the same. The average axle load selection criterion (6.5 t – 8.5 t) is very similar to the selection of the higher 30% of the GVM range used in the FTR Method [14].

Selected Trucks are defined here as Eligible Trucks with average axle loads in the range of 6.5 t – 8.5 t.

It was found that the average monthly truck-tractor load, T_{TT}, for Selected Trucks was stable at approximately 21.8 t for the test sample of well calibrated screening WIMs, with a coefficient of variation of only 1.2%. This indicated that T_{TT} was suitable as a target for post-calibration. The average T_{TT} of 21.8 t is almost the same as the FTR Method calibration constant of 21.7 which indicates that it corroborates the findings from the historical development process.

The T_{TT} of Selected Trucks at good operating WIMs were also found to be very stable, with a typical standard deviation in the order of 1.7 t. This proved to be a valuable indicator of whether the random variation in WIM measured truck tractor loads were consistent with that of installations in good condition and could hence be used as a data quality check. The concept is discussed further in Section 7.2.

6.3.3 Truck Tractor Calibration Procedure

The calibration procedure must yield the appropriate adjustment factor, k_{TT}, for which the average truck-tractor mass of Selected Trucks is equal to the pre-determined target value, using the following formula:

$$k_{TT} = \frac{T_{trgt}}{T_{TT}} \tag{10}$$

Where:

k_{TT}	Calibration factor, from Truck-Tractor Calibration method
T_{TT}	Average truck-tractor mass of Selected Trucks
T_{trgt}	Target truck-tractor mass (default value 21.8 t)

Owing to the fact that loading forms part of the selection criteria for Selected Trucks, the appropriate calibration factor, k_{TT}, for a set of WIM data should be determined using the following iterative process:

Step 1: Identify Selected Trucks and calculate first estimate of k_{TT}

Step 2: Apply k_{TT} to raw data

Step 3: Calculate adjustment for residual systematic error, using $k_{adj} = T_{trgt} / T_{TT}$

Step 4: Refine k_{TT} by multiplying with k_{adj}

Step 5: Repeat steps 2-4 until Step 2 yields $k_{adj} = 1.000$

Typically, the equilibrium value is reached within 6 iterations.

The monthly calibration factors for each WIM are applied to the axle loads in the RSA files using the following formula:

$$D_{Ai} = k_{TT} \cdot D_{Ri} \tag{11}$$

Where:

D_{Ai}	Adjusted Dynamic load of axle i
D_{Ri}	Raw Dynamic load of axle i
k_{TT}	Calibration factor from TT Method

6.3.4 Accuracy of the Truck Tractor Method

The monthly calibration factors obtained from the TT Method (k_{TT}) were compared to those from the Weighbridge-Linked Method (k_{WL}) to evaluate the accuracy of the TT Method. The comparison was done for the period October 2006 to June 2008.

Figure 15 shows the monthly comparison of k_{TT} with k_{WL}. If the two methods corroborated each other perfectly, all points would have been on the identity line. The graph indicates that monthly discrepancies between k_{TT} and k_{WL} were always less than 5%.

A statistical interpretation of the accuracy of the TT Method, using the Weighbridge-Linked Method as reference, is provided in Table 6-3.

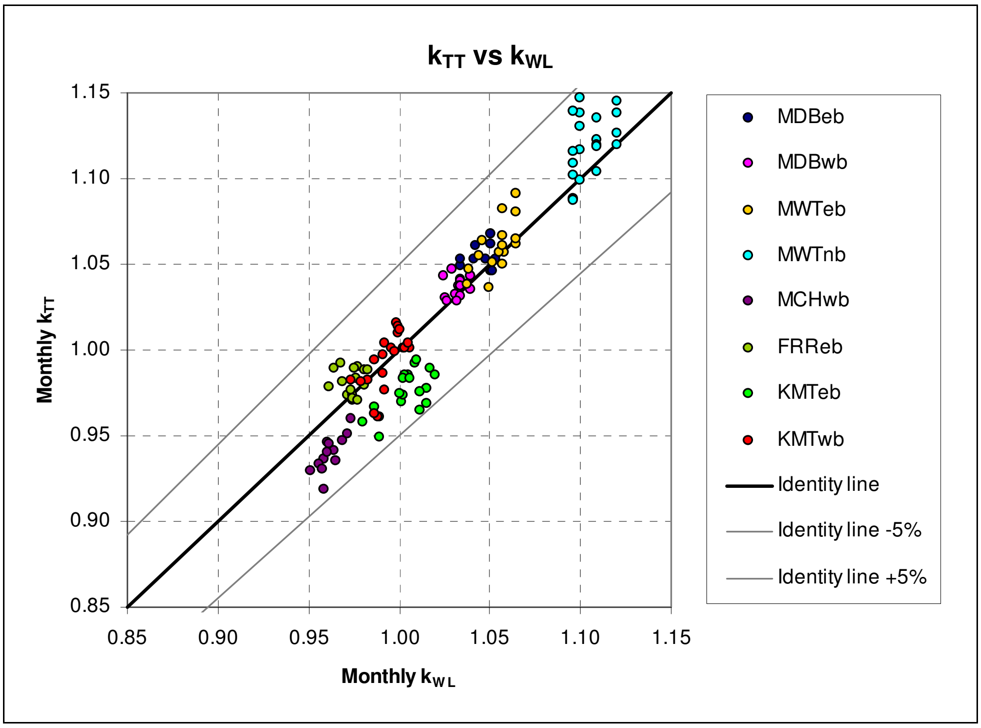


Figure 15: Comparison of k_{TT} with k_{WL}

Table 6-3: Discrepancies of Calibration Factors obtained from TT Method

WIM Station	Description	Discrepancy in Monthly k_{TT}, using k_{WL} as reference (%)	
		Mean	**St Dev**
3040 – Mid-East WIM	Typical National Freeway	0.69%	0.81%
3041 – Mid-West WIM	Uphill (4%) National Freeway	0.40%	0.71%
3042 – Mid-Wit eastbound WIM	Major Provincial Arterial	0.56%	1.07%
3043 – Mid-Wit northbound WIM	Regional Road, lightly trafficked	1.48%	1.54%
3045 – Machado WIM	Typical National Highway	-2.36%	0.71%
3046 – Farrefontein WIM	Downhill (3%) National Highway	0.74%	1.01%
3047 – Komati eastbound WIM	National Road, speed reduction	-2.82%	0.97%
3048 – Komati westbound WIM	Medium speed screening lane	0.03%	1.17%
ALL COMBINED		**-0.12%**	**1.82%**

The mean accuracy of the TT Method is acceptable, and it confirms that it can be used successfully for post-calibration.

The low standard deviation of monthly errors in k_{TT} also shows that it is repeatable. It was found that, for stable WIMs with monthly samples of more than 200 Selected Trucks, the k_{TT} for any month is within 3% of the average k_{TT} for the five preceding months. This concept was further developed as a data quality check – see Section 7.4.

7 DATA QUALITY MANAGEMENT

7.1 Introduction

There are two approaches to WIM data quality management. One approach is to ensure that the physical WIM installation (pavement, frame, sensor, feeders, computer hardware and software) conforms to some predetermined standard and to subsequently accept that WIM data quality is acceptable. The second approach is to measure data against predetermined norms to determine whether it is acceptable. The second approach is far more direct, but the complication is that it is difficult to define suitable data characteristics for testing and to establish norms for acceptability.

The philosophy of this report is that data quality should be determined using the data itself. The "health" of a WIM is therefore judged by its "symptoms". If a WIM fails the data quality checks, the root of the problem must be investigated on site. This report is thus primarily focussed on the needs of the WIM data user who must interpret whether WIM results are reliable. Service providers will be more inclined to use the first approach, viz. to keep the physical installation in good order, but should also be guided by warning signs that emanate from analysis of data.

Routine data quality checks were developed in conjunction with the TT Calibration Method, and are discussed further in this chapter.

7.2 Standard Deviation of F_{TT} and T_{TT}

It was found, through the analysis of WIMs where known failures occurred, that the standard deviations of T_{TT} and F_{TT} can be used as an indicator of unacceptably large random error and thus serve as criteria for disqualification.

The standard deviation of T_{TT} is calculated a follows:

$$S_{TTT} = \sqrt{\frac{\sum\left(T_{TTi} - T_{TT}\right)^2}{N-1}} \tag{12}$$

Where:

S_{TTT} Standard deviation of T_{TT}

T_{TT} Average Truck-Tractor mass of Selected Trucks

T_{TTi} Truck-Tractor mass of Selected Truck i

N Number of Selected Trucks

Similarly, the standard deviation of the front axle loads from Selected Trucks, F_{TT}, is calculated a follows:

$$S_{FTT} = \sqrt{\frac{\sum \left(F_{TTi} - F_{TT}\right)^2}{N-1}} \tag{13}$$

Where:

S_{FTT} Standard deviation of F_{TT}

F_{TT} Average front axle mass of Selected Trucks

F_{TTi} Front axle mass of Selected Truck i

N Number of Selected Trucks

The purpose of reviewing the standard deviations of T_{TT} and F_{TT} is not to identify outliers, but instead to identify cases where the WIM likely produced bad data. The typical statistical practice to identify statistical outliers as those outside 2.5 or 3.0 standard deviations from the mean is therefore not appropriate here. Instead, more than 750 data months from approximately 50 WIMs (of which the history of each WIM and the quality of data was known) were analysed to determine the standard deviations of T_{TT} and F_{TT} and to develop threshold values for these parameters that would identify bad WIM data as such.

The qualification of data as “Good” or “Bad” is somewhat subjective since accurate pavement measurements and WIM error distributions were not always available. WIMs that are considered to be producing Good data are typically those that would achieve at least COST 323 accuracy class C(15) if a random sample from the road (R2 sample, Type I repeatability) was used to verify the accuracy. These WIM systems are considered to be accurate enough to be used at least for statistical traffic data collection.

Data from WIMs with known pavement failures, logger errors, loose frames or severe levelness problems were considered to have produced “Bad” WIM data. These WIMs are not considered fit for statistical traffic data collection. In most cases the WIMs identified as Bad were subsequently replaced, or the installation or pavement improved.

In the absence of absolute certainty about the quality of data, the data from some WIMs were described as "Suspect". It was believed that the data from these WIMs were dubious owing to poor riding quality, excessive temperature dependence or logger instability, but the problems were not severe enough that data could be described as "Bad".

Figure 16 below shows a plot of monthly S_{TTT} vs S_{FTT} for various WIMs. The graph was developed using recent data from the N1 North, Bakwena, N4 East and N3 toll roads – detailed information is attached as Appendix C. The plots represent months of Good WIM data (green dots), Suspect data (grey dots) and Bad data (red dots). The warning and rejection thresholds will be discussed later.

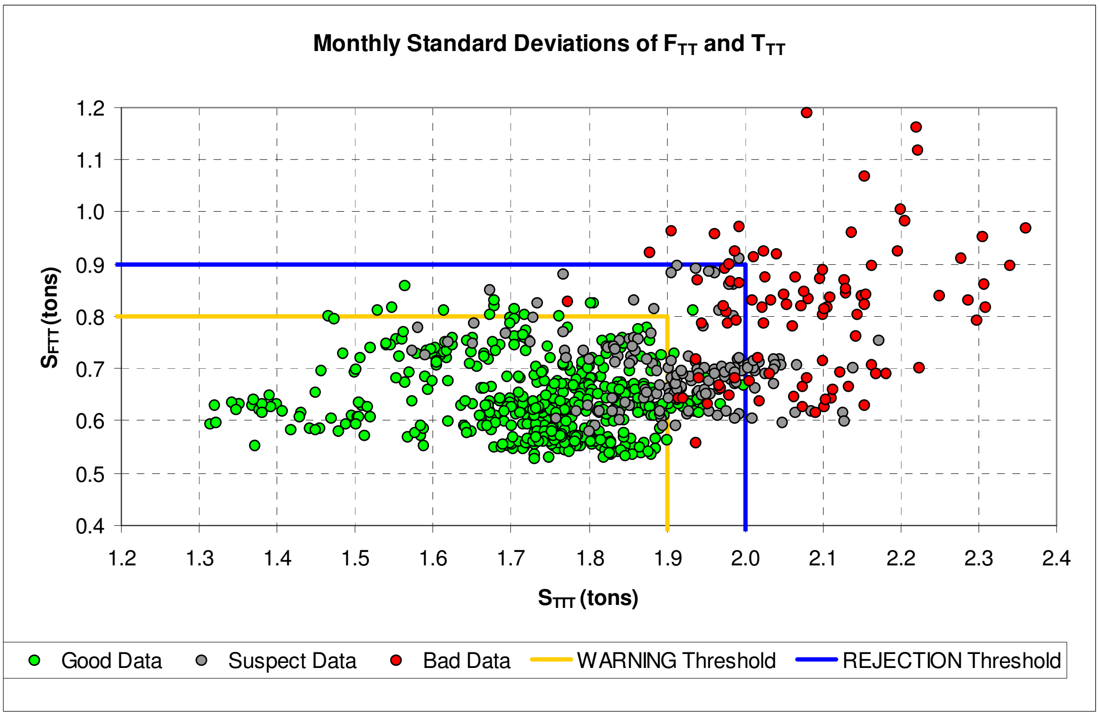


Figure 16: Standard Deviations of F_{TT} (S_{FTT}) and T_{TT} (S_{TTT})

It must be noted that additional Bad data files were analysed to improve on the characterisation thereof and the split between Good, Suspect and Bad data is therefore not a reflection on the quality of data obtained from Toll Concession Projects. A statistical analysis of the data is given below.

Table 7-1: Statistical Analysis of S_{FTT} and S_{TTT}

Description		Good Data	Suspect Data	Bad Data
Sample		527	159	97
S_{TTT}	5th percentile	1.471	1.722	1.934
	50th percentile	1.756	1.913	2.081
	95th percentile	1.893	2.046	2.315
S_{FTT}	5th percentile	0.545	0.605	0.631
	50th percentile	0.625	0.696	0.823
	95th percentile	0.759	0.864	1.077

Two types of thresholds are shown on Figure 16, viz. the warning threshold and the rejection threshold. These thresholds were developed with consideration of consumer's risk and supplier's risk. Consumer's risk may be defined in this application as the probability that the WIM data user accepts Bad data. Supplier's risk is the probability that the WIM vendor supplies Good data that is rejected by the client. The objective here is to minimise the customer's risk without being unreasonable to the supplier. Probability distributions of S_{FTT} and S_{TTT} were plotted to serve as a basis for the selection of thresholds – see Figure 17 and Figure 18 below. The warning thresholds were selected such that the supplier's risk would be below 5% and the Rejection thresholds such that supplier's risk would be negligible.

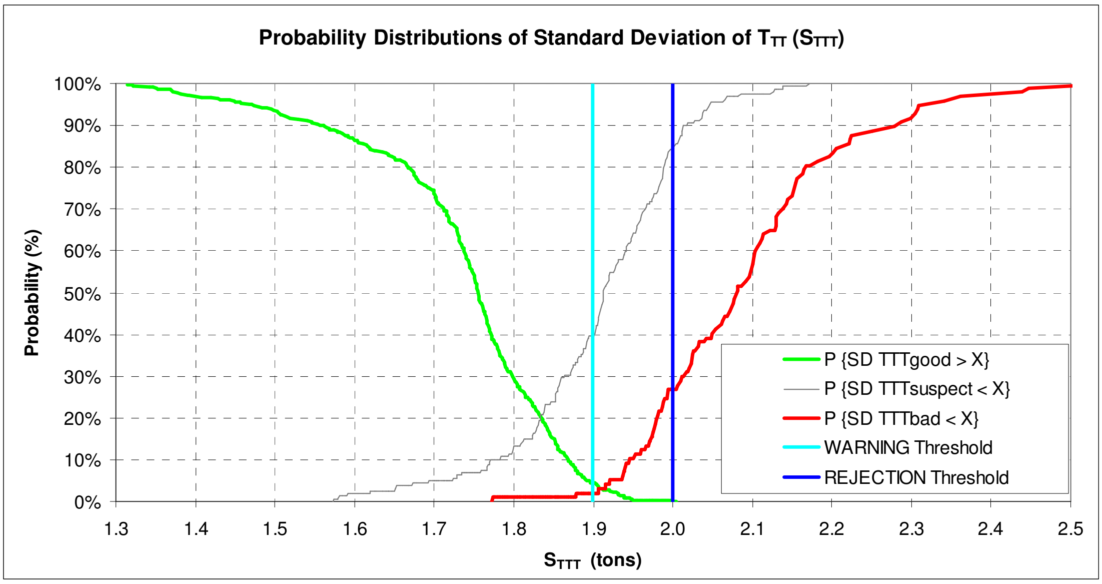


Figure 17: Probability Distributions of S_{TTT}

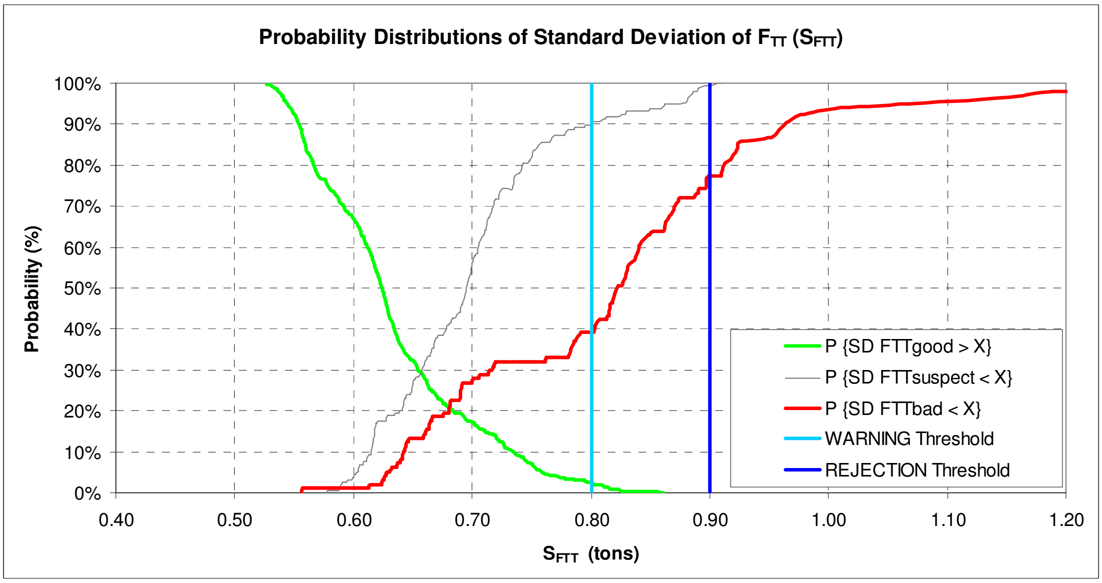


Figure 18: Probability Distributions of S_{FTT}

The cluster of red dots (Figure 16) strays away from the green dots primarily in the horizontal plane. S_{TTT} is thus a better indicator of data quality than S_{FTT}. The large consumer's risk associated with the thresholds for S_{FTT} is therefore not a major threat since more than 90% of data that fail the thresholds do so based on S_{TTT}. It should further be noted that the author recommended a rejection threshold value of 1.0 for S_{FTT} in an earlier publication [(14)] – this value can be regarded as a basic safety net in view of the dominance of S_{TTT}.

The threshold values for S_{FTT} and S_{TTT} are to be applied in combination. The combined impact on consumer's risk and supplier's risk is shown below.

Table 7-2: Consumer's Risk and Supplier's Risk

Type of Risk	Description of Risk	Risk (%)	
		WARNING Thresholds for S_{FTT} and S_{TTT}	**REJECTION Thresholds for S_{FTT} and S_{TTT}**
Consumer's Risk	Accept Bad Data	0%	22%
Supplier's Risk	Reject Good Data	7%	0%

The following strategy may be adopted in practice:

- The ***rejection thresholds*** may be used to control the performance of the supplier. The rejection criteria are sufficiently favourable to the supplier that they can be applied with theoretically 0% risk of being unreasonable. The consumer, however, runs a 22% risk of accepting data that is in fact Bad.

- The ***warning thresholds*** may be used to eliminate the risk of using Bad data for reporting and to identify data files that should rather be disregarded for this purpose. Approximately 7% of Good data may consequently be discarded in the process.

The table above only applies to Good and Bad data. The so-called Suspect data must still be accounted for. As mentioned, Suspect data are generally accepted to be of an inadequate accuracy for statistical purposes, but cannot be classified as Bad. The terminology of consumer's risk and supplier's risk is perhaps not appropriate and will therefore not be used here. The impact of the Warning and Rejection criteria on Suspect data is summarised below.

Table 7-3: Impact of Warning and Rejection Thresholds on Suspect Data

Description	**Risk (%)**	
	WARNING Thresholds for S_{FTT} and S_{TTT}	**REJECTION Thresholds for S_{FTT} and S_{TTT}**
Accept Suspect Data	36%	84%
Reject Suspect Data	64%	16%

From Table 7-3 it can be seen that 84% of Suspect data will still be accepted when applying the Rejection Thresholds, which indicates their leniency. If the Warning Thresholds are used, less than 40% of Suspect data will be accepted. This appears to be an acceptable number as there is no exact boundary between Good and Suspect data – the aim of the data quality checks is simply to distinguish WIM data that are almost certainly Good from those that are almost certainly Bad.

7.3 Spread of WIM Error

Section 7.2 uses S_{TTT} and S_{FTT} as an indicator of whether a WIM produces Good or Bad data. The spread of WIM error could serve as a more direct indicator of WIM data quality, but in practice it is difficult to conduct a detailed analysis of WIM error if the WIM is not used in conjunction with a static scale.

Even though it is not foreseen that WIM error could be used on a routine basis as a data quality check, it would be useful to know how WIM accuracy relates to other parameters used for data quality control. The relationship between S_{TTT} and spread of WIM error was thus investigated.

The screening WIMs on the N4 East and those at the Heidelberg TCC on the N3 were used to determine the spread of WIM error on axle units. Vehicle records were discarded if errors on GVM exceeded 50% as it was assumed that they were created though incorrect linking by the scalemasters or that the vehicle clipped the WIM sensor. Outliers, defined here as errors on GVM exceeding three standard deviations from the mean, were also discarded – even though they may not have a significant impact on the calculation of systematic error, they have a profound impact on the calculation of the standard deviation of WIM errors.

The spread of WIM error on GVM was reported in terms of the COST 323 Specification. The monthly sets of linked WIM-weighbridge records represented large Type II, R2 samples (see Section 2.1.2). For large samples, COST 323 requires a confidence level, π_0, of 94.3 % that WIM errors are within the predefined confidence intervals that define the respective accuracy classes (see Table 2-5). It was assumed for the purpose of this evaluation that WIM error on GVM was approximately Normally distributed. The two-sided standard normal deviate (also known as the z-value) that corresponds with a confidence level of 94.3 % is 1.903, which means that the confidence interval of WIM error on GVM achieved by a WIM, $\delta_{achieved}$, is approximately ±1.903 standard deviations wide. The threshold values of δ for GVM in Table 2-4 were used to relate the spread of errors at respective WIMs to COST 323 accuracy classes. The other test elements (axle units, single axles and axles within groups) were not evaluated.

WIMs were calibrated on a monthly basis using the Weighbridge-Linked method before the standard deviations of errors on axle units, S_{TTT}, and the spread of errors on GVM, $\delta_{achieved}$, were calculated.

The graph below shows a plot of S_{TTT} vs $\delta_{achieved}$ for 67 data months as well as the COST 323 accuracy classes (defined in terms of δ, Table 2-4). An attempt was made to include a variety of Good and Bad WIM data – see Appendix D.

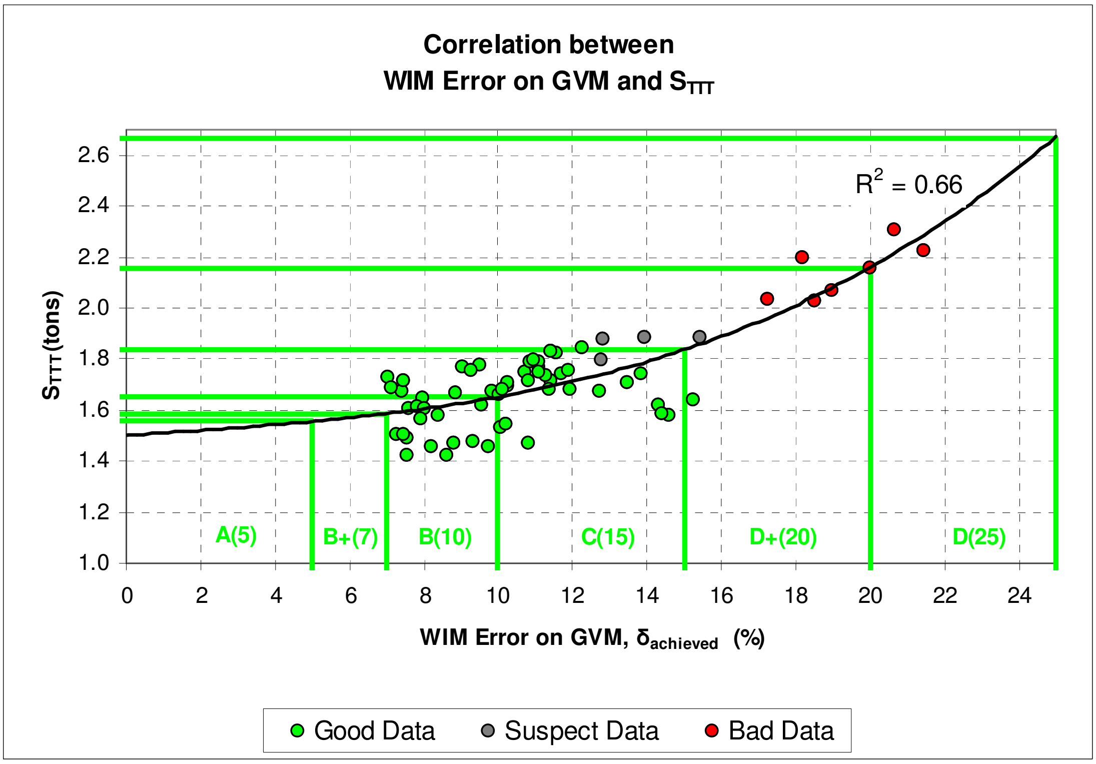


Figure 19: Correlation between WIM Error and S_{TTT}

It can be seen from the graph that:

- S_{TTT} increases with the spread of WIM error.
- S_{TTT} below 1.6 t is very good, and generally only achievable with a WIM of at least Class B(10) accuracy.
- WIM of least Class C(15) accuracy produce S_{TTT} generally lower than 1.85 t. A Class C(15) WIM should thus comfortably pass the warning thresholds suggested in Section 7.2.
- The Bad WIMs investigated still produced data of Class D+(20) and D(25) accuracy. Class D(25) is not considered fit for statistical purposes, and Class (D+(20) should be viewed with caution because it represents the transition between Good and Bad data. It appears that both the Warning and Rejection thresholds of S_{TTT} fall within the Class D(20) accuracy envelope.

7.4 Stability and Level of Calibration Factor, k_{TT}

Two aspects of monthly calibration factors play a role in WIM data quality. They are:

- the stability of monthly calibration factors; and
- the value of the calibration factors.

It was found from the WIM data used in the development of the TT Method that, for stable WIM systems with more than 200 Selected Trucks per month for post-calibration, the calibration factor rarely differed by more than 3% from the average of the calibration factors for the preceding 5 months. The standard deviations of these differences were almost always less than 1.5%. This feature may be used as an indicator to identify possible malfunctioning of the WIM or accelerated pavement failure.

An example where the rapid change in k_{TT} successfully indicated accelerated failure of a WIM is shown below. The Van Reenen southbound WIM frame started to come loose from the pavement in January 2008. The WIM deteriorated rapidly during February, and was removed in March. It was reinstalled in May, and the calibration settings were adjusted in July. A more gradual drift in k_{TT} was observed from January up until May 2009. It was later found that the pavement failed and the WIM frame lost its binding with the surrounding pavement. Much of the deterioration occurred during the dry winter months and the gradual drift in k_{TT} indicates that the pavement never went into a moisture accelerated distress phase.

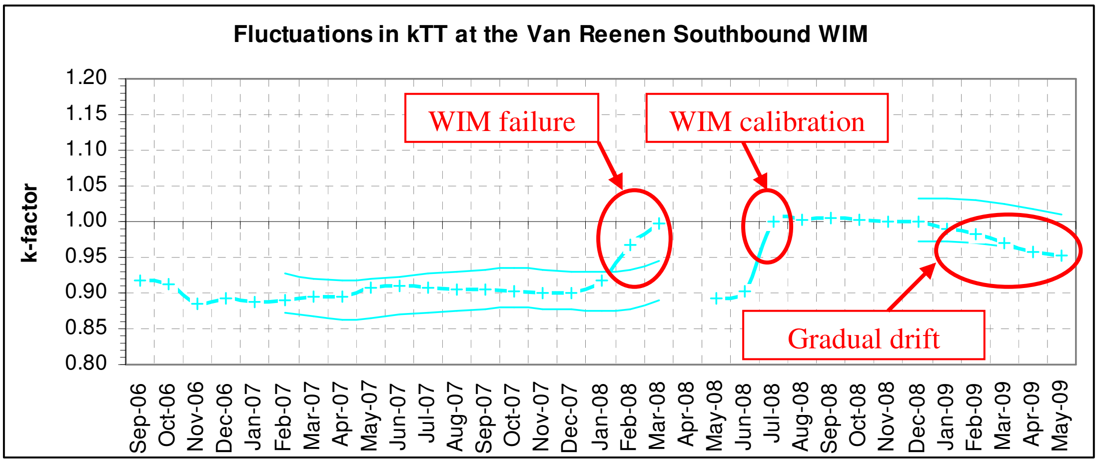
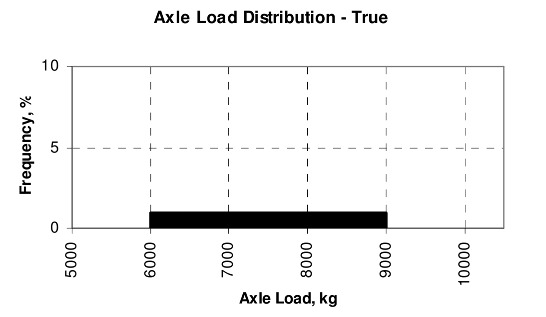


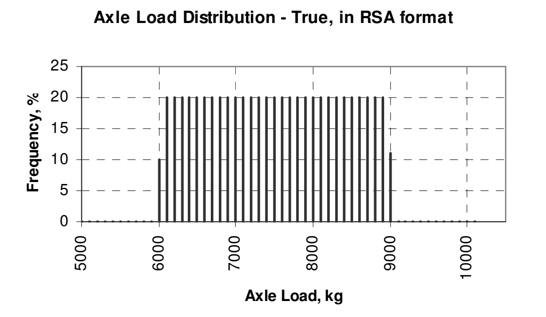
Figure 20: Fluctuations in k_{TT} as an Indicator of WIM Failure

The value of k_{TT} is not an indicator of the quality of WIM data, but factors very different from 1.0 have a noticeable impact on post-calibrated WIM data owing to the rounding of axle loads. The RSA data format only allocates three characters per axle load. Loads are therefore recorded as multiples of 100 kg, e.g. an axle load of 6 723 kg will be rounded to 6 700 kg and recorded in the RSA format as “067”. The rounding of axle loads for the purpose of the RSA format produces a discrete distribution of axle loads as opposed to the true continuous distribution.

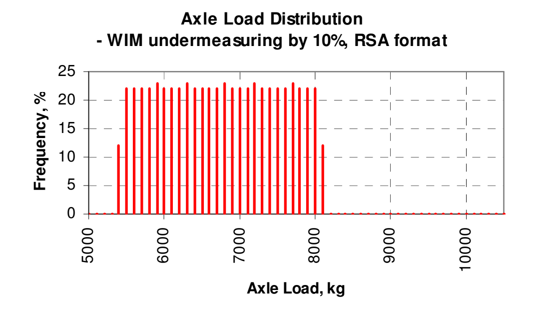
The rounding of axle loads is particularly detrimental for WIMs that are poorly calibrated. To illustrate the problem in a simplified manner, an artificial uniform distribution of 'true' axle loads was created. The distribution contains 601 axle loads from 6 tons to 9 tons – all axle loads are thus 5 kg apart. This distribution was used to test the effect of the rounding of axle loads to accommodate the RSA data format, under- or over-measuring by the WIM (excluding the effect of random error) and post-calibration (e.g. using the TT Method). The graphs below indicate the impact of rounding on data from WIM systems that under- or over-measure by 10%. Further examples are attached as Appendix E.



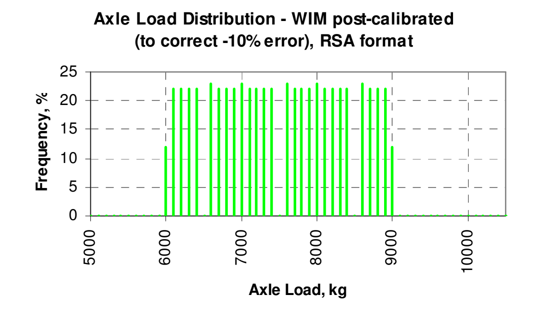
True Axle Load Distribution



True Axle Load Distribution in RSA Format

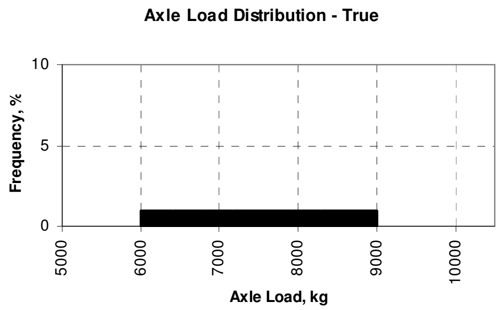


Axle Load Distribution by WIM (Error = -10%)

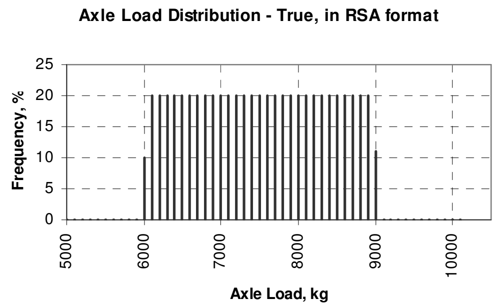


Axle Load Distribution by WIM, Post-Calibrated

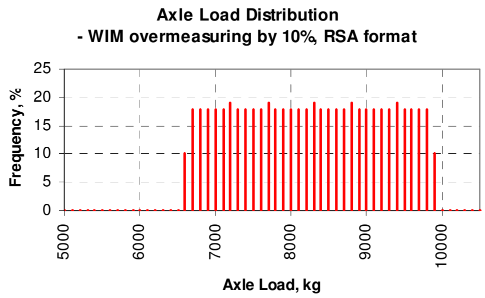
Figure 21: Rounding of Axle Loads; Post-Calibrating an Under-Measuring WIM



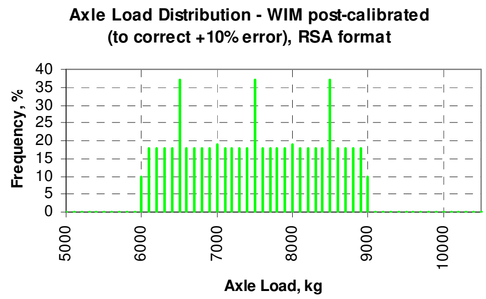
True Axle Load Distribution



True Axle Load Distribution in RSA Format



Axle Load Distribution by WIM (Error = +10%)



Axle Load Distribution by WIM, Post-Calibrated

Figure 22: Rounding of Axle Loads; Post-Calibrating an Over-Measuring WIM

From the results above and those in Appendix E it was found that:

- For under-measuring WIMs, the number of utilised 100 kg bins is reduced. If a WIM is under-measuring by 10%, the axle load distribution will shrink to the left and approximately 10% less bins will contain records. The opposite applies for over-measuring WIMs.
- When the miss-calibration is corrected through post-calibration and a new RSA file is created, the distribution of axle loads extends from 6 tons to 9 tons again. Some bins are however empty for the WIM that was under-measuring, whilst the number of entries in some bins are approximately doubled for the WIM that was over-measuring.
- The number of empty bins (for under-measuring WIMs) and doubled bins (for over-measuring WIMs) in post-calibrated data increases with the systematic error of the WIM. Every 10th bin is severely affected for a WIM that is miss-calibrated by 10%.
- All axle load bins are affected. Additional axle loads in a double bin were drawn from the other less affected bins, and similarly, empty bins are created through the distribution of axle loads over other bins.

The percentage of severely distorted bins is approximately the same as the percentage miss-calibration. For a WIM that is under-measuring by 20% one out of five bins (i.e. 20%) will be empty and the other bins will have approximately 20% too many records in the post-calibrated RSA file.

From the discussion above, it is evident that under- or over-calibration of a WIM is detrimental to the axle load distribution. The post-calibration procedure is effective in placing the distribution of axle loads in the correct position, but bins will be distorted. A WIM should therefore be set as accurately as possible in the field. It is the experience of the author that a WIM can readily be set to within 10% of the true calibration factor in the field, and that this norm may be insisted upon.

7.5 Typical Front Axle Loads

From the analysis of data from more than 50 WIMs over an extended period of time, it was found that the majority of high-speed WIMs, once calibrated using the TT Method, produce average front axle loads, F_{TT}, of 5.6 t – 6.6 t for Selected Trucks. This range is too wide to be used as a quality check, but stratified ranges have proven to be useful for the characterisation of a WIM.

The graph below shows the front axle loads of a number of WIMs on the N1 North, N3, Bakwena and N4 East toll roads for May 2009. It can be seen that the WIMs where more than usual rearing is expected owing to acceleration or upgrades have F_{TT} typically between 5.6 t and 5.9 t, while those where reversed rearing is expected owing to deceleration or downgrades have F_{TT} typically between 6.3 t and 6.6 t. The remaining sites are scattered mostly between 5.8 t and 6.3 t. The variation in F_{TT} for the 'typical' WIMs can generally be explained in retrospect. For example, the F_{TT} at Mantsole and Heidelberg that are on the higher side can be explained because these WIMs are in dedicated screening lanes where vehicles are coasting at medium speed. On the lower end of the spectrum are stations like Pietersburg and Kranskop where trucks are motoring at high speeds on long and straight sections of road.

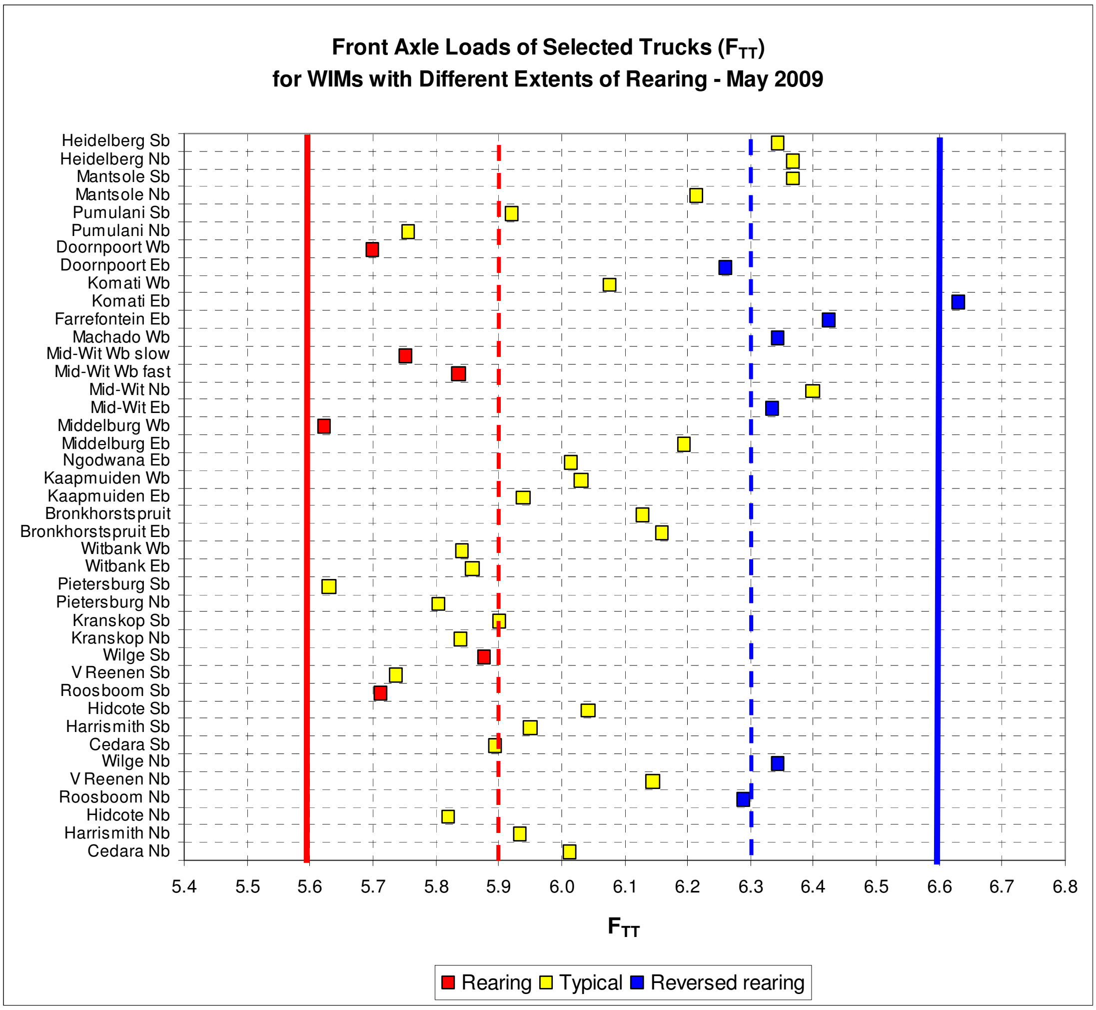


Figure 23: Typical Ranges of F_{TT}

Table 7-4 provides typical ranges of F_{TT} for WIMs with different rearing characteristics. These are not meant to be used as rejection criteria, but rather to evaluate whether the value of F_{TT} corroborates the anticipated rearing characteristic of a particular WIM. If the F_{TT} of a particular WIM is totally different from the expected rearing characteristic (particularly if it falls outside of the 5.6 t to 6.6 t range), the WIM should be inspected and the calibration of the WIM should be revisited and redone if appropriate.

Table 7-4: Typical Ranges for Front Axle Load, F_{TT}

Description of Rearing	Characteristics	F_{TT}
Rearing	Increased transfer of load from steering to driving axles owing to upgrade, acceleration or motoring.	5.6 t – 5.9 t
Typical	Neutral site where trucks travel at constant speed over WIM installed in straight, flat section of road	5.9 t – 6.3 t
Reversed Rearing	Negligible load transfer, or transfer of load from driving onto steering axle owing to downgrade, braking etc.	6.3 t – 6.6 t

7.6 Lane Discipline

A useful by-product of the FTR method (see Section 6.2) is that it gives an indication of the extent to which poor lane discipline and consequent clipping of sensors results in under-measuring of axles. Even though the FTR is not used in the Truck-Tractor calibration procedure, it should still be plotted for quality control purposes.

Clipping of sensors mostly occurs on the outer edges of the half-lane sensors that are widely used in South Africa, because trucks tend to stray over the yellow line and into the paved shoulder of the road. The result is that a part of the wheel clips the sensor and passes partly on the adjacent pavement, or on the less sensitive outer edge of the sensor.

The FTR of an Eligible Truck is the front axle load, F, expressed as a proportion of the truck-tractor load, T. The FTR is evaluated for not only the Selected Trucks, but for all Eligible Trucks. If the FTRs of individual trucks are plotted against their respective average axle loads, the points on the graph form a banana-shaped cluster. For WIMs with excellent lane discipline, hardly any points stray from the cluster. In contrast, a protrusion of points breaks away from the cluster at WIMs where many vehicles clip the WIM sensor. When an Eligible Truck clips the sensor on the outside (left-hand side), the steering axle (single wheel) is severely under-measured, while the under-measurement of the driving axles' dual wheels is less pronounced because only the outer wheel clips the sensor. The result is an FTR that is uncharacteristically low for the truck's average axle load. Whilst severe clipping may result in the front axle being missed totally (and the vehicle record subsequently being rejected based on illogical axle configuration), less severe clipping can result in a reduction in measured axle loads that may not be sufficient to be indicated as a bad record.

A typical clipping identification line, called the C-line, was developed through inspection of many WIMs with known good and problematic lane discipline, and the vehicles below this line are considered to give a good estimate of how many Eligible Trucks have been under-measured because they clipped the WIM sensor. A vehicle is considered to have clipped the sensor if the following is true:

$$FTR_i < \left[0.45 - (0.0375) \cdot (AvgAx_i)\right] \tag{14}$$

Where:

FTR_i F_i / T_i for Eligible Truck i

F_i	Front axle load of for Eligible Truck i
T_i	Truck-tractor load of for Eligible Truck i
$AvgAx_i$	Average axle load of Eligible Truck i

The graphs below show examples of protrusions (nicknamed 'hernias') through the C-line for WIMs with excellent and problematic lane discipline respectively:

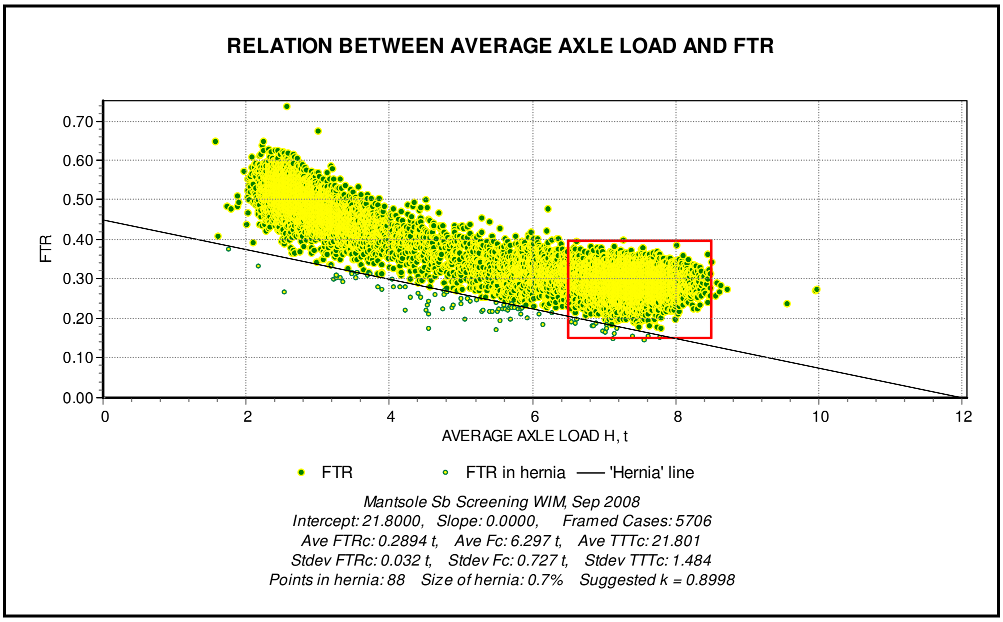


Figure 24: Protrusion through C-line for WIM with Excellent Lane Discipline

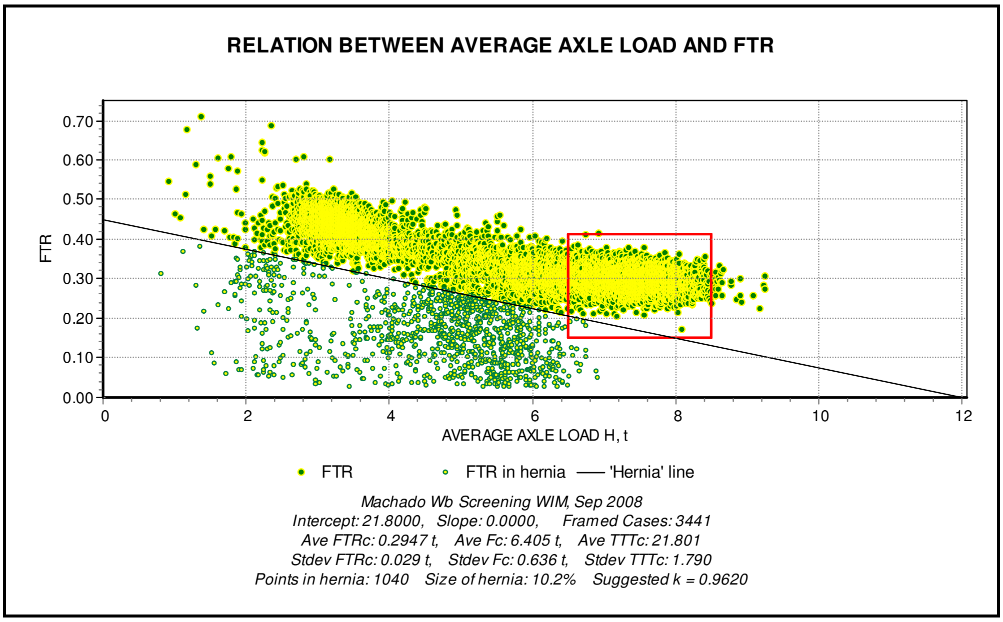
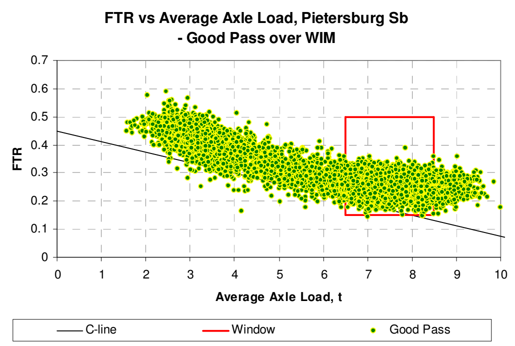


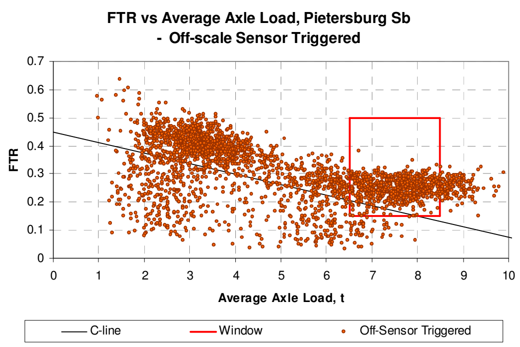
Figure 25: Protrusion through C-line for WIM with Problematic Lane Discipline

A more direct test of how well the protrusion through the C-line indicates sensor clipping was performed using data from the Kranskop and Pietersburg WIMs (capacitive sensors, left wheel path) on the N1 Toll Road where off-scale sensors are installed to identify vehicles of which a part of the wheel/s travelled over the outer 15 cm of the sensors. Not all vehicles that activated the off-scale sensors were necessarily under-measured as the less sensitive outer edges of the sensors are narrower than 15 cm. What can be said with confidence is that those vehicles that did not activate the off-scale sensors could not have been under-weighed as a result of poor lane discipline.

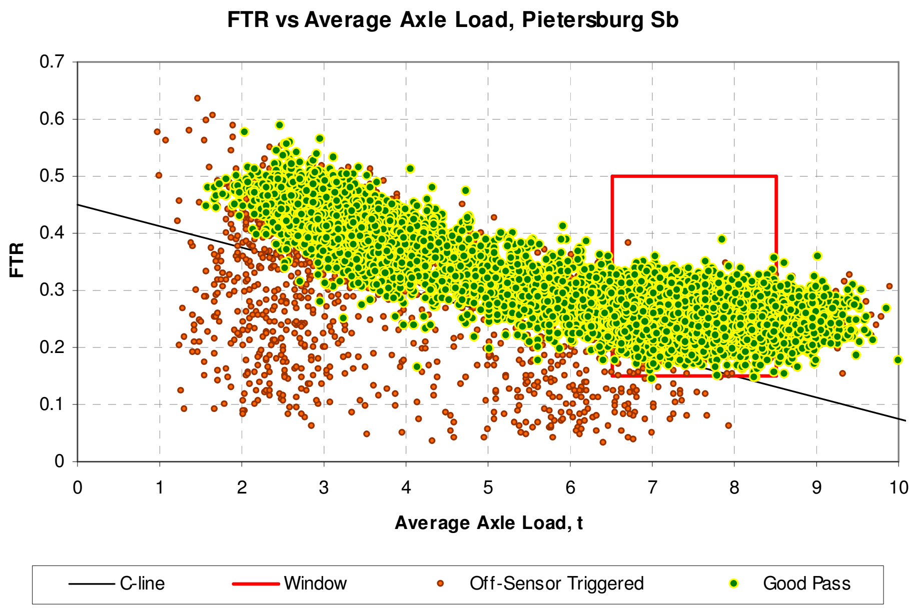
The figures below show plots of FTR vs Average Axle Load for good passes and passes that triggered the off-scale sensors at the Pietersburg southbound WIM in August 2008. The lane discipline at this site is regarded as being undesirable.



Good Passes over WIM



Off-Scale Sensor Triggered



All Passes over the WIM Combined, Pietersburg Southbound

Figure 26: Protrusion through C-line for WIM Equipped with Off-Scale Sensors

Figure 26 indicates that hardly any of the vehicles that passed centrally over the WIM failed the C-line clipping test, whilst the protrusion through the C-line is very noticeable for the sub-population of trucks that triggered the off-scale sensor. Roughly 80% of the vehicles at the Pietersburg southbound WIM that triggered the off-scale sensors still produced data that appeared to be good – the off-scale sensors therefore eliminated more records on account of suspected sensor clipping than what was necessary.

Graphs of FTR vs Average Axle Load for both directions of travel at the Kranskop and Pietersburg WIMs in August 2008 are attached as Appendix F. The protrusion through the C-line was less than 1.5 % for all four these WIMs after the vehicles that triggered the off-scale sensors were removed.

The extent of clipping may be defined as the percentage of all eligible 6- and 7- axle trucks below the C-line, i.e. the percentage of trucks that satisfies Equation (14). The extent of clipping is calculated as follows:

$$Clipping(\%) = 100 \cdot \left(\frac{E_h}{E_N} \right) \qquad (15)$$

Where:

E_h Number of Eligible Trucks below the C-line

E_N Total number of Eligible Trucks

The following table gives typical ranges of clipping, as established from the analysis of approximately 50 WIMs with lane discipline ranging from excellent to very poor.

Table 7-5: Typical Ranges for Clipping

Clipping	Lane Discipline	Typical WIM Characteristics
< 2%	Excellent	Dedicated screening lanes, enforced lane discipline, narrow shoulders.
2% – 6%	Typical	Typical HSWIM sites, straight flat sections, paved shoulders.
6% – 10%	Problematic	Up- or downgrades, mild curves, accesses in vicinity of WIM.
> 10%	Unacceptable	WIM positioned incorrectly, poor / no lane marking, deliberate clipping of screening WIMs by truck drivers.

It is important to note that the protrusion through the C-line generally occurs below the average axle load range of 6.5 t to 8.5 t (see Figure 25). This is because vehicles that clipped the sensor are unlikely to register high gross vehicle masses. The important realisation here is that the TT Calibration Method is not negatively affected by poor lane discipline and clipping of WIM sensors.

With suggestion from Dr SC van As, the author developed and tested thresholds for front axle load and average axle load for trucks with different numbers of axles. The intention was to use these thresholds as filters to identify individual records in a database that are likely to have been created by vehicles that clipped the WIM sensor. The data from the Kranskop and Pietersburg WIMs (i.e. with off-scale sensors) were used for this purpose.

Plots of front axle load vs average axle load were used to develop thresholds for these two parameters by looking at the difference between graphs from vehicles that activated the off-scale sensors and those that did not. The plots for all vehicle types (by total number of axles) are shown in Appendix G, and those for 7-axle trucks are repeated below.

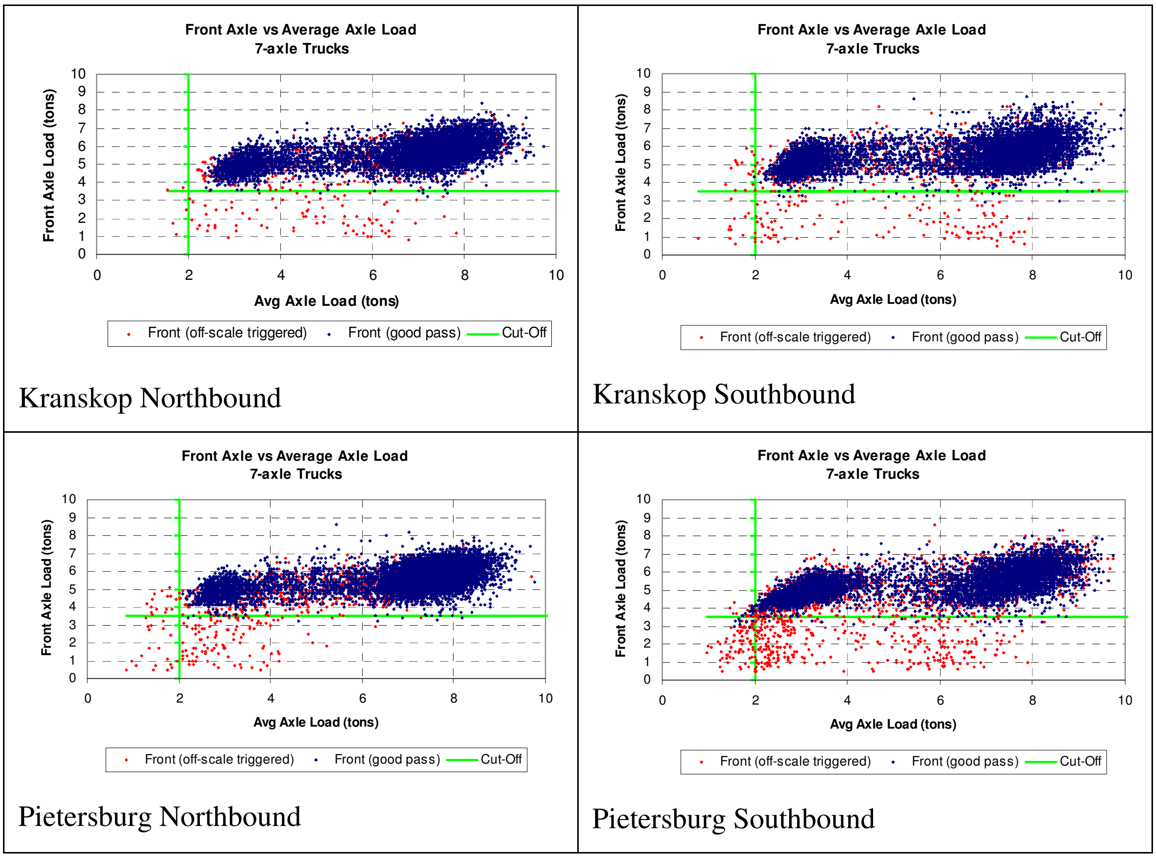


Figure 27: Front Axle vs Average Axle Load, 7-axle Trucks

It can be seen from the graphs above that points from good WIM passes produced dense clusters from which minimum values for front axle and average axle load could be developed. Many of the points from vehicles that clipped the off-scale sensors broke through these threshold lines. Lane discipline at Pietersburg southbound was noticeably worse than at the other sites.

Threshold values for front axle and average axle load were developed for all truck types, classified by the number of axles. A vehicle record is to be rejected for probable sensor clipping if any one of the following two equations are satisfied:

$$A < A_{\min} \tag{16}$$

$$F < a + (b \cdot A) \tag{17}$$

Where:

A	Average axle load of truck
A_{min}	Minimum acceptable A
F	Front Axle load of truck
a, b	Constants

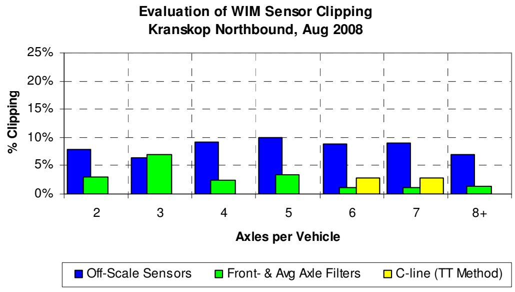
The values of A_{min} are as follows:

A_{min} = 1.75 t	for 2-axle trucks
A_{min} = 2.00 t	for all other trucks

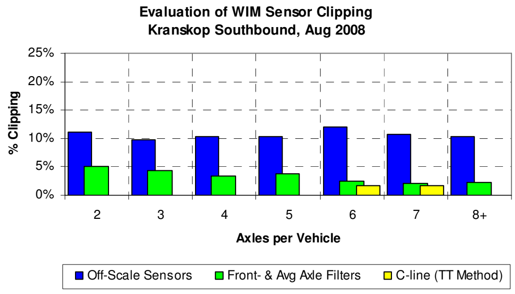
The values of a and b depend on the number of axles:

a = 0.0 and b = 0.50	for 2-axle trucks
a = 1.0 and b = 0.35	for 3-axle trucks
a = 1.5 and b = 0.25	for 4-axle trucks
a = 3.5 and b = 0.00	for 5+ axle trucks

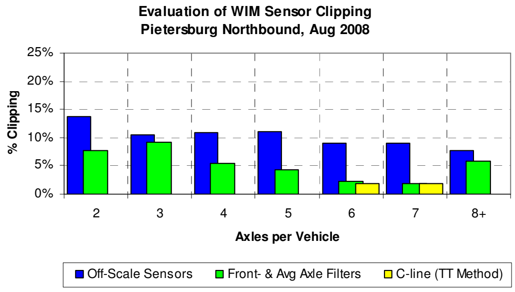
The thresholds described above were used to calculate the percentage of probable clipping at the Kranskop and Pietersburg WIMs. These percentages were compared to those calculated as part of the TT Method (see Equation 14 and 15) and the results from the off-scale sensors. The results are shown below:



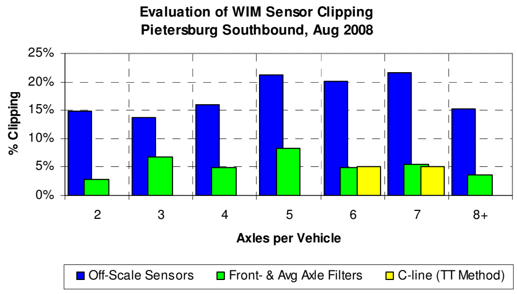
Kranskop Northbound



Kranskop Southbound



Pietersburg Northbound



Pietersburg Southbound

Figure 28: Evaluation of WIM Sensor Clipping using Three Methods

The following can be deduced from the graphs above:

- The off-scale sensors appear to be conservative. The percentage of vehicles that activated the off-scale sensors were excessive, and more than half of them still produced axle load measurements that followed typical patterns observed for good passes.
- Contrary to the expectation that bigger articulated trucks are more inclined to travel in the shoulder and clip the WIM sensors, the percentage of different types of trucks that activated the off-scale sensor were generally similar.
- The percentages of sensor clipping for different vehicle types according to the front and average axle load filters are not always stable. 3-axle trucks are indicated as clipping cases more often than other types. Some of these rejections appear to be 2-axle trucks pulling light single axle trailers. Whilst this may be unfair, this indication of clipping is necessary to identify 3-axle rigid trucks that truly clipped the sensor.
- The C-line method generally corroborates well the tests based on front and average axle loads, albeit only for 6- and 7-axle trucks (that are used in the TT Calibration methodology). The C-line can be used as a warning sign to show when lane discipline changes or becomes problematic particularly at sites where the percentage of long heavy vehicles (typically five or more axle) exceeds 50% of trucks.

The percentage clipping from the TT Method can thus be used as a routine data quality check. To eliminate individual vehicle records that in all probability clipped the WIM sensor, the threshold values of front and average axle loads for different vehicle types must be used. Off-scale sensors can be used as a corrective measure at problematic sites to ensure that only the best vehicle passes are used for analysis.

7.7 Impact of Temperature on WIM Measurements

A seasonal fluctuation in the monthly k_{TT} became visible for all the WIMs on the N1 North and N3 Toll Roads. The fluctuation was greater for the N1 WIMs (Mikros capacitive sensors) than for the N3 WIMs (PAT bending plates). Examples of these monthly fluctuations are shown below.

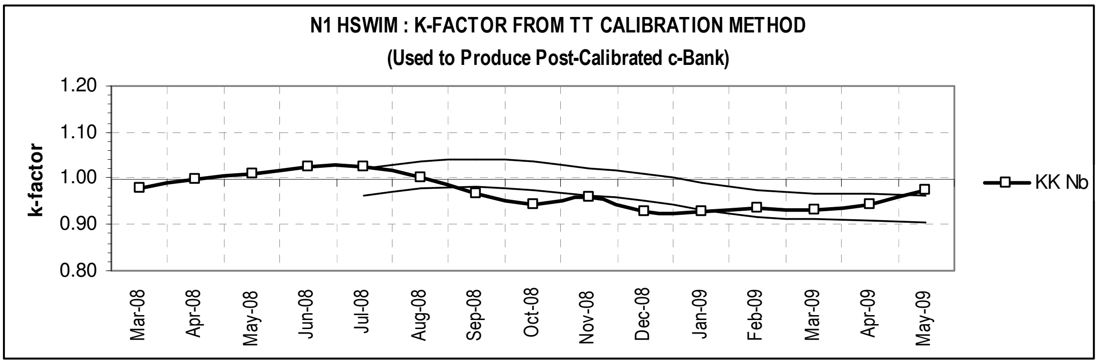


Figure 29: Monthly Fluctuation of k_{TT}, N1 Kranskop Northbound

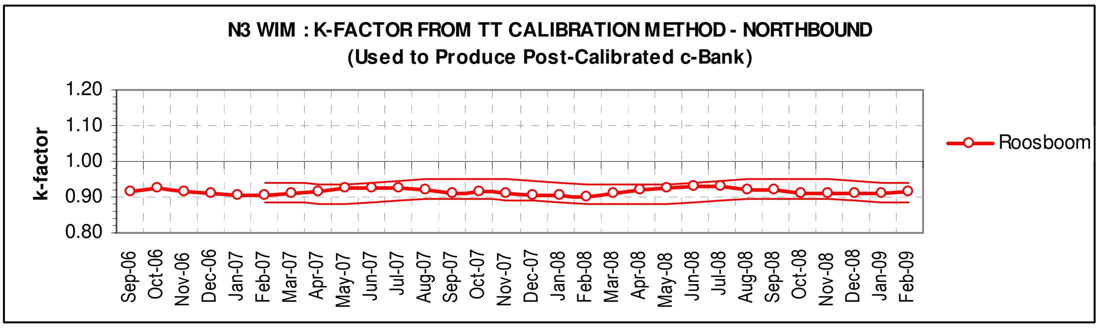


Figure 30: Monthly Fluctuation of k_{TT}, N3 Roosboom Northbound

It can be seen from the above that k_{TT} was higher in winter and lower in summer which pointed towards the possible temperature dependence of WIM measurements. The phenomenon was more pronounced at all four of the N1 WIMs than anywhere else, and resulted in cases where the data quality check on the stability of k_{TT} was failed.

Selected monthly RSA files for the Pietersburg and Kranskop (Mikros capacitive sensors), Roosboom (PAT bending plates) and Pumulani (IRD bending plates) WIM stations were modified such that the k_{TT} factor could be determined for different 2-hour periods in a typical day. The percentage difference between the k-factors for respective 2-hour periods and the k-factor for all periods combined (i.e. for the entire month) were plotted and are shown on the graphs below. The daily fluctuation in k_{TT} strengthened the suspicion that there was a correlation with temperature.

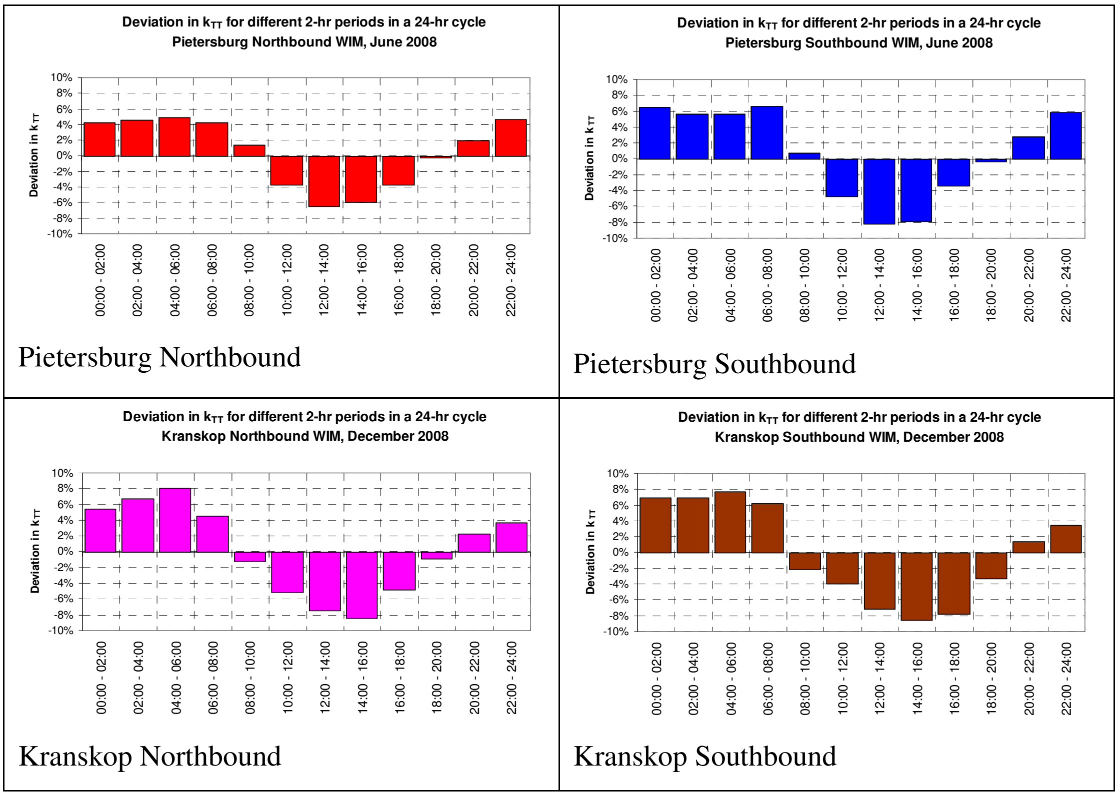


Figure 31: Daily Fluctuation in k_{TT} at WIMs with Capacitive Sensors

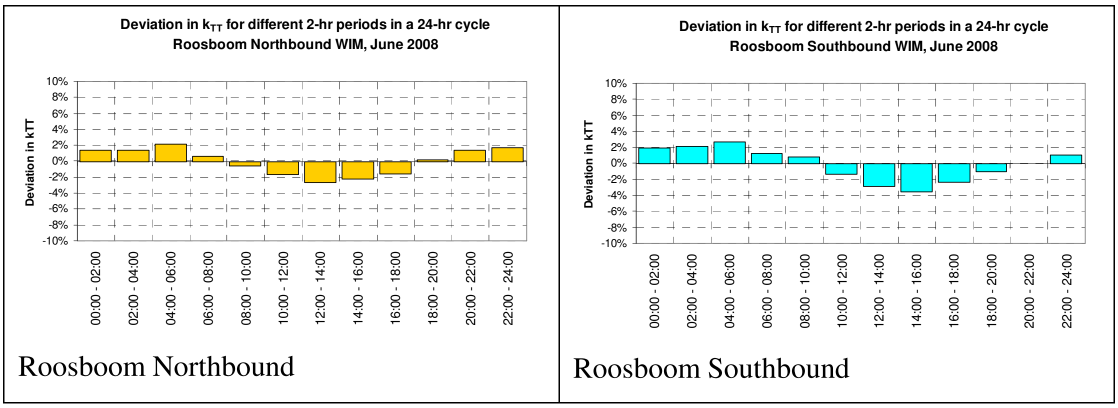
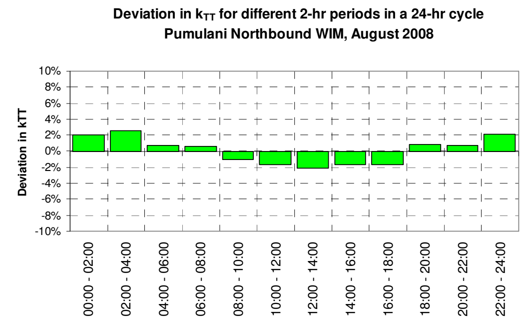
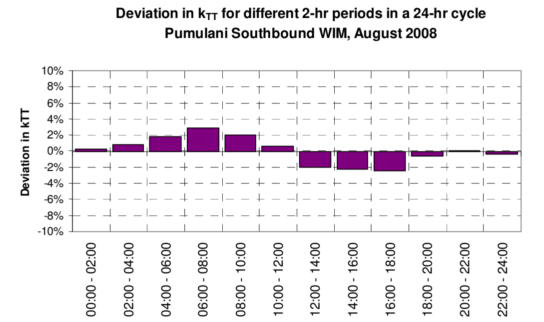


Figure 32: Daily Fluctuation in k_{TT} at WIMs with PAT Bending Plates



Pumulani Northbound



Pumulani Southbound

Figure 33: Daily Fluctuation in k_{TT} at WIMs with IRD Bending Plates

It can be seen that k_{TT} for the capacitive sensors at Pietersburg and Kranskop deviated by as much as 8% from the monthly k_{TT} during hot or cold periods. The deviation at Roosboom and Pumulani (PAT and IRD bending plates) was less significant, but still clearly visible.

Mikros Systems made further data available for the purpose of evaluating the residual temperature dependence of the Kranskop and Pietersburg installations on the N1. WIM data were submitted for the period January to June 2009 with the temperature of the WIM sensor for each vehicle record additionally provided. A summer, autumn and winter month were analysed for each of the WIMs. Monthly data were sorted into temperature bins, and the TT Method was applied to the subsets of data to obtain k_{TT} factors at varying temperatures. For every month, data was first recalibrated such that k_{TT} for the 30 ºC bin would be equal to one, so that possible drift in WIM measurements would not impact on the evaluation of temperature effects. The graph below shows the relationship between k_{TT} and temperature.

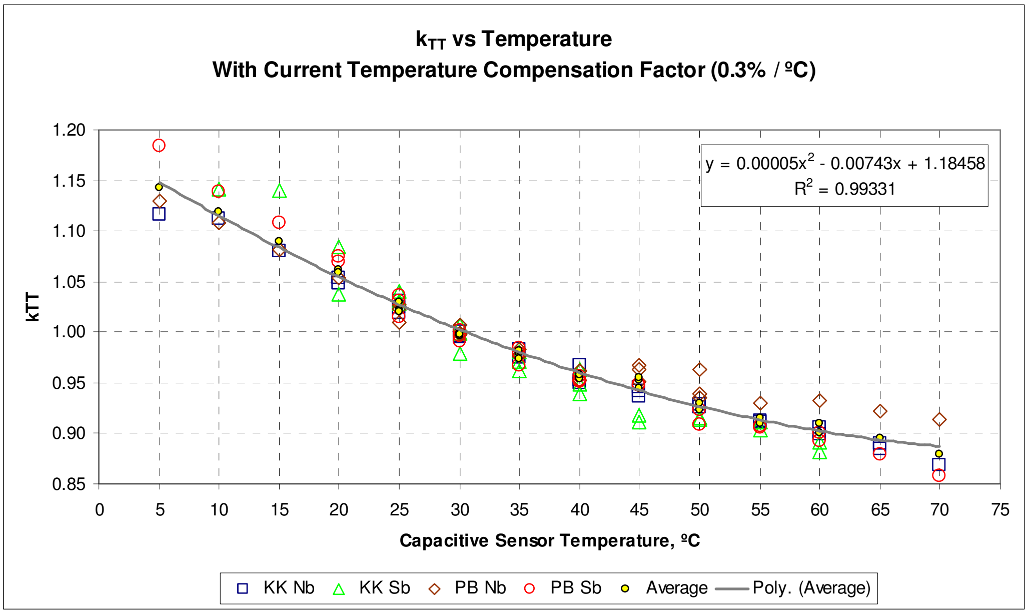


Figure 34: Relationship between k_{TT} and Temperature at the N1 WIMs (Current)

From the above it is clear that k_{TT} changes with temperature, and that the relationship is not linear. At the lower temperature range the k_{TT} changes at a rate of almost 0.7% / ºC, and at a rate of approximately 0.3% / ºC at the higher temperature range. The observed temperature dependence is the residual effect after an adjustment of 0.3% / ºC has already been made by the supplier (Mikros Systems).

The temperature compensation algorithm can be adjusted for historic data as the raw binary data were archived, and these contain the sensor temperature for each measurement. Based on the evidence above, Mikros entered into investigations of their own and as a first trial increased the temperature compensation factor from 0.3% / ºC to 0.6% / ºC. Figure 35 shows that the reduction in the residual temperature dependence was reduced as a result, yet the non-linearity of the temperature dependence still presents a problem and further adjustment is required.

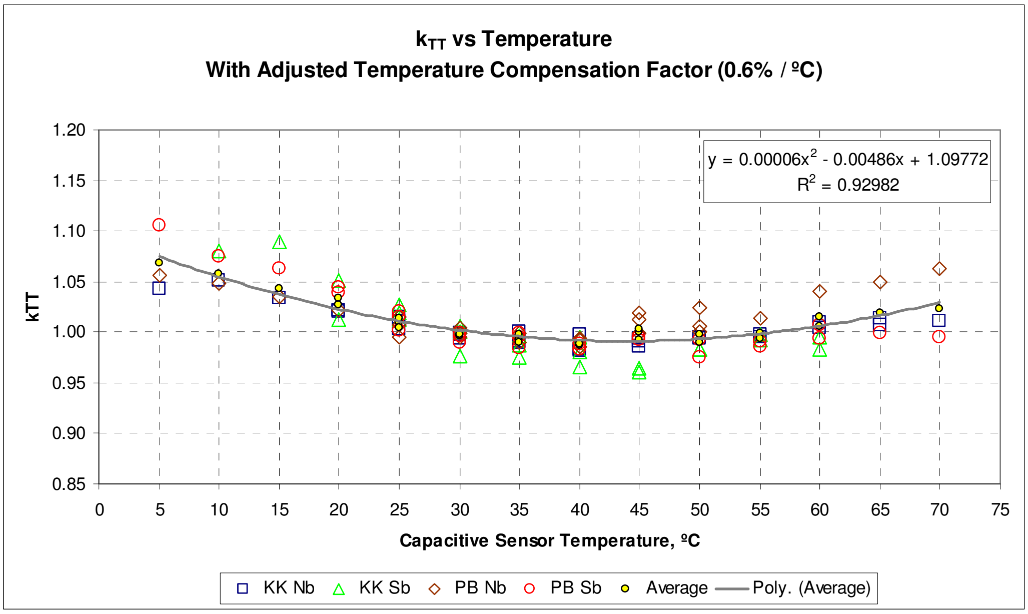


Figure 35: Relationship between k_{TT} and Temperature at the N1 WIMs (Adjusted)

Further research is required to determine whether the apparent temperature dependence should be attributed to the WIM sensor itself, the roadside electronics, different dynamic effects when a vehicle's tyres are hot or cold, different effects of hot (more pliable) or cold (stiffer) asphalt layers or yet something else. All four capacitive sensors reacted in approximately the same manner and the apparent temperature dependence of these installations is in the order of two to three times worse than for any of the bending plate installations that were evaluated.

According to their manufacturers, bending plates are not temperature dependent. The typical temperature range in which WIMs operate generally has a negligible impact on measurements. Some temperature correction was however found to be necessary for bending plates operating in temperatures below +5 ºC in Europe [(10)].

Capacitive sensors are temperature dependent. Corrections are made to recorded axle load measurements based on the temperature of the WIM sensor for every measurement. The correction for the Mikros sensors is currently 0.3% per degree Celsius and is based on laboratory testing as part of the development of the sensors. It has been shown that further corrections can be made, even in retrospect, to compensate for possible inadequacies of the current correction factors or the combined effect of external temperature related effects.

It was mentioned earlier in the report that the focus of the document was the data user and how to manage and interpret WIM data. From this point of view it is adequate to acknowledge that some temperature dependencies may be present for some WIM installations, and would be revealed by a data quality check as simple as the k-factor stability check discussed in Section 7.4. If the monthly k-factors remain within the acceptance envelope, the temperature dependence may be considered to be within acceptable limits. Seasonal fluctuations should be pointed out to the service provider nonetheless.

7.8 Implementation and Testing

The practical implementation of a WIM calibration and quality control process is necessary to determine their true value. From current international practice it is evident how various WIM users have refined standards such as ASTM E1318 and COST 323 to fit the characteristics of different WIM systems based upon practical experience of the success thereof. The practical implementation of the TT Method and its associated quality checks will over time show whether South African users perceive it as being adequately accurate, simple and robust to be used for statistical data collection at WIM sites on a routine basis. Further advances and refinements may result from the practical testing phase.

The FTR Method and its associated data quality checks were already used on a trial basis during 2008, and the value thereof was demonstrated to toll concessionaires. When further refinement and testing culminated in the TT Method it became apparent that SANRAL would accept it as a National norm. The TT Method and its associated data quality checks were consequently accepted and implemented on the N1 North, N3, Bakwena, and N4 East Toll Road projects in the first half of 2009.

The calibration module of the TT Method (i.e. the procedure to determine the calibration factor, k_{TT}) was accepted by SANRAL, and it is currently being incorporated into their model that quantifies the cost of overloading on toll concessions. The principles of using the standard deviations of front axle and truck tractor loads and average front axle loads of Selected Trucks as data quality checks was also adopted, but the threshold values are still being debated. The first trial version of the software was made available in the second half of 2009, and it is expected that further trials and refinements will continue into 2010.

It is believed that National consensus on how to calibrate and evaluate the quality of WIM data will result in the collection of more stable and credible WIM data in future.