STATISTICAL ANALYSIS OF VEHICLE LOADS MEASURED WITH THREE DIFFERENT VEHICLE WEIGHING DEVICES

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ABSTRACT

This study introduces a new scale for weighing individual tyres of slow moving vehicles. The new technology is referred to as "Stress - In – Motion" or SIM and is statistically compared with an existing Weigh-In-Motion (WIM) scale (DAW 50) and a Multi-Deck Static scale at the N3 Traffic Control Centre (N3-TCC), near Heidelberg. The raw data was validated for quality, resulting in a total usable sample of 2 297 trucks (12 830 axles) from the SIM device. The validated paired data indicated that the SIM data compares very linearly to the mass weight results of both the DAW 50 and Static scales. However, the SIM data underestimated the average gross vehicle Mass (GVM), or gross combination mass (GCM) by 6 to 7 per cent compared to the DAW 50 and Static scales, at levels of significance of α = 1, 5 and 10 per cent. Similar findings were made on the paired data of the axle groups and single axle mass weights. The relative prediction limits of the SIM device ranges between +/- 0.6 tonnes to +/- 4.1 tonnes, depending on the confidence level and mass weight configuration. The precision of the scales were also studied using the well known repeatability (r) and Reproducibility (R) concepts. Four dedicated trucks were measured repeatedly on different days over the three scales. Although standard mass weight limits for r and R were achieved at a α = 5 per cent level of significance, more replica measurements are needed to further improve on the qualification of the precision limits of the SIM system, as well as for the Static and DAW 50 scales.

1. INTRODUCTION AND BACKGROUND

The loading that vehicles exert on pavements plays a vital part in the deterioration of the structural and functional capacity of the road. It also influences the safety of the vehicles, especially when vehicles are operated under overloaded and/or inappropriately loaded conditions. In order to better manage vehicular loads and their distribution on South African road pavements, systems of weighbridges are being utilized to monitor vehicular loads (or mass weights)[1] and also for the prosecution of those offenders that operate overloaded vehicles.

Bosman (2004) indicated that South Africa has approximately 253 000 registered heavy vehicles (HVs) with a Gross Vehicle Mass/Gross Combination Mass (GVM/GCM) greater than 3.5 tonnes, of which approximately 26 000 are buses. This study compares a new development for the enhanced (mass) weighing of individual tyres of slow-moving vehicles, that could be compared relatively easily with normal axle mass weights, axle group mass weights and GVM/GCM of heavy vehicles.

[1] In this paper the output from the scales are given as "mass weight" in kg or Tonnes. 1 Tonnes = 1 000 kg. When the term "load" is used the unit is Newton, i.e. load = (mass weight) x g, where g = 9.806 m/s^2).

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CSIR Transportek undertook the development of a device for the measurement of tyre-pavement interaction during 1992 (De Beer et al, 1997). The idea was to capture the tyre-pavement contact stresses under a slow moving tyre (< 6 km/hr) for the sole purpose of improved mechanistic-empirical road pavement design and analysis. Elaborate testing and validations programs were performed with the locally developed equipment, dubbed the Stress-In-Motion (SIM) technology, analogous to the better-known Weigh-In-Motion (WIM) technology (De Beer and Fisher, 1999, De Beer et al 1999, 2002, 2004a, 2004b).

2. FIELD STUDIES AND APPROACH TO DATA ANALYSES

Verification studies under controlled loading and inflation pressure using the South African Heavy Vehicle Simulator (HVS) indicated that the three dimensional tyre-pavement contact forces/stresses inside the contact area are highly non-uniform. These contact stresses depend on the load/inflation pressure combinations and, to a lesser extent, on the type of tyre (De Beer et al, 1997, De Beer and Fisher, 2000). This information challenge the traditional assumption of the late 1960s that a tyre load could be represented by a uniform circular disc of average contact stress, normally taken as equal or 30 per cent less to the inflation pressure, as described by Van Vuuren (1974). In addition, only vertical stress of the tyre is considered by most pavement design methodologies, whereas the SIM technology demonstrated the existence of lateral and longitudinal stresses within the tyre-pavement contact area. Under high loading and relatively low inflation pressure, these transverse stresses can be very high, and should be taken in consideration during the structural design process of the pavement.

The first field experiment with a full SIM system (4 SIM pads to measure all tyres of a single axle) was done at the Mantsole Traffic Control Centre on the N1 (De Beer and Fisher, 1999). This experiment was funded by the South African National Roads Agency Limited (SANRAL, or the Agency) and CSIR Transportek.

In May 2002, manufacturing and installation of a permanent test pit for the SIM MK IV system on the N3 -TCC site (northern lane) were successfully completed. In 2003 CSIR Transportek was approached by the Agency to assist with a comparative testing program between the Weigh-In-Motion (WIM) scale (DAW 50) and the Multi - Deck Static scale (Static) at the N3 Traffic Control Centre (N3-TCC) near Heidelberg using the new Stress-In-Motion (SIM) Mk IV system (Heidelberg WIM Experiment, 2003). The fieldwork for these measurements, was completed by November 2003.

The aim of this study is to enable comparisons between the *paired* data sets of the actual single axle mass weights, axle group mass weights and the Gross Vehicle Mass (GVM), and/or the Gross Combination Mass (GCM) measured with the SIM system and those measured with the DAW 50 and Static scales (De Beer et al, 2004c). The mass weight results (quality rated 1 and 2) from the three weighing devices were compared by means of the general descriptive statistical method and the analysis of variance (ANOVA) at levels of significance (α) of α = 1, 5 and 10 per cent. ANOVA is a statistical method used to test the significance of differences between two or more population means (SAS, 1990). The Fisher's Least Significant Difference test (LSD) was used to locate where the differences occurred between the different scales (Anderson et al, 2003). The relative precision of each of the scales was also studied using the well known concepts of repeatability (r) (same day/same truck/same scale) and Reproducibility (R) (different days/ same truck/ same scale) (BS 5497, 1997; ISO, 1986).

2.1 Methodology and validation criteria

The approach was to install the SIM Mk IV system in a dedicated test pit, in series with the WIM scale (DAW 50) at the N3-TCC. All four SIM pads were used simultaneously so that the total mass weight per axle, axle group and vehicle could be obtained for each truck, based on the individual tyre mass weights measured.

Truck traffic was diverted from the N3 into the Static and DAW 50 and SIM measuring lanes. A total of 3 047 trucks (17 770 axles) were measured with the SIM over a 6-week period at the N3-TCC during this study. The raw data were then validated for quality. Approximately 75 per cent of the measured data were rated as Good (2) to Very Good (1), resulting in a total sample of 2 297 trucks (12 830 axles) from the SIM device. For the purpose of statistical comparisons of the results from the SIM, DAW 50 and Multi – Deck Static scales, only *paired* data with quality ratings of 1 and 2 were used. These are reported on in this paper.

Table 1: 4 - Point data rating scale used to rate the quality of the SIM measurements on site (De Beer et al, 2004c)

Rating Scale	Classification	Criteria
1	Very Good (VG)	All tyres 100 per cent over SIM measuring pads
2	Good (G)	Only some (2 to 3) tyres partly missing the SIM pads
3	Poor (P)	A number of tyres partly missing the SIM pads (typically from the same axle group)
4	Very Poor (VP)	Many tyres partly off the SIM for one or more axle groups

The test programme also included obtaining limit replicate data from three dedicated trucks provided by SANRAL. These trucks did several repetitions over all three measuring devices on different days. In addition, the CSIR Deflectograph was also used on different days for comparisons of replicate runs. The sole requirement by SANRAL in this case was to statistically compare actual measured mass weights obtained on the SIM, DAW 50 and the Multi – Deck Static scales at N3-TCC. The following data from each of the trucks measured are compared and discussed in this paper:

- Single axle mass weights (SIM, DAW 50);
- Axle group mass weights (SIM, DAW 50, Multi - Deck Static);
- Gross Vehicle Mass (GVM) (SIM, DAW 50, Multi - Deck Static) and
- Gross Combination Mass (GCM) (SIM, DAW 50, Multi - Deck Static);

3. THE THREE SCALES USED

3.1 Stress-In-Motion (SIM) scale

The Stress-In-Motion (SIM) or device is illustrated in Figure 1. It consists of 4 individual pads arranged in the test pit to accommodate each tyre of a vehicle moving over it. Measurements are done at slow creep speeds (6 km/h or less). The mass weight of each tyre is measured through an array of multi-axial strain gauged sensors during the single pass of a tyre. The speed of each axle is individually measured and used in the calculation of the tyre mass weights. A more detailed description is given by De Beer et al (1997). By summing the individual tyre mass weights, the axle and axle group mass weights are obtained and by summing the axle group mass weights, the GVM/GCM of a particular vehicle is obtained.

Figure 1: In-situ configuration of the SIM Mk IV (4 pads) system ready for testing at N3-TCC

Figure 2: DAW 50 in position (permanent installation) at the N3-TCC (in front of the SIM system)

Figure 3: Multi - Deck Static Weighbridge scale (permanent installation) at the N3-TCC

3.2 DAW 50 Scale

The DAW 50 Weigh-in-Motion (WIM) scale (or weighbridge system) used at N3-TCC is illustrated in Figure 2. It is used for the static or dynamic weighing of gross mass weights and axle mass weights, also at low passing speeds (up to 6 km/h) (PAT, 1995). The mass weight is measured by 4 shear beam load cells. The system is supported by a heavily reinforced steel concrete slab. (It should be noted that the same test pit design was used for the SIM system at this test site).

3.3 Multi-Deck Static Weighbridge Scale

The Multi-Deck Static scale (Static) is illustrated in Figure 3. It comprises an 18m x 3m flat unit, consisting of four independent steel decks to allow the static weighing of the axle group mass weights and GVM/GCMs of vehicles.

4. STATISTICAL ANALYSIS: GVM/GCM

4.1 Descriptive Statistics

The descriptive statistics analysis tool generates a report of univariate statistics for input data, and provides information about the central tendency, variability of the data, characteristics of the distribution relative to the normal distribution, etc. (Anderson et al, 2003; SAS, 1990). The descriptive statistics of the GVM/GCM measurements rated 1 and 2 are given in Table 2.

Table 2: Descriptive Statistics of the GVM/GCM measured with the three scales relative to one another (Units: Tonnes)

Descriptive Statistics	SIM	STATIC *	SIM	DAW 50	STATIC	DAW 50
Mean	34.447	36.887	34.246	36.291	39.016	38.492
Standard Error	0.366	0.395	0.407	0.438	0.402	0.399
Median	36.144	38.980	35.920	38.400	43.420	42.560
Mode	6.419	15.100	50.802	14.960	15.100	14.960
Standard Deviation	15.800	17.056	15.753	16.976	16.918	16.787
Sample Variance	249	290	248	288	286	281
Kurtosis	-1.430	-1.432	-1.436	-1.455	-1.303	-1.324
Skewness	-0.219	-0.264	-0.217	-0.236	-0.447	-0.429
Range	58.108	57.300	58.108	56.320	62.180	56.320
Minimum	3.197	3.460	3.197	3.420	3.460	3.420
Maximum	61.305	60.760	61.305	59.740	65.640	59.740
Sum	64105	68646	51403	54473	69097	68169
***Paired* data Counts (n)**	**1861**	**1861**	**1501**	**1501**	**1771**	**1771**

* Static = Multi-Deck Static weighbridge at N3-TCC.

Table 2 indicates (amongst others) that the ample variance of the GVMs/GCMs measured on the SIM device is a somewhat lower than those measured on the STATIC and DAW 50 scales. The central values (mean and median) of the SIM are slightly lower than those of the STATIC or DAW 50 scales. The characteristics of the GVM/GCM data from all three scales give an indication of a relatively flat distribution (negative kurtosis), which is skewed (negative skewness) towards lower mass weight values compared with a normal (Gaussian) distribution. The GVM/GCM distributions obtaned are graphically represented in Figure 4.

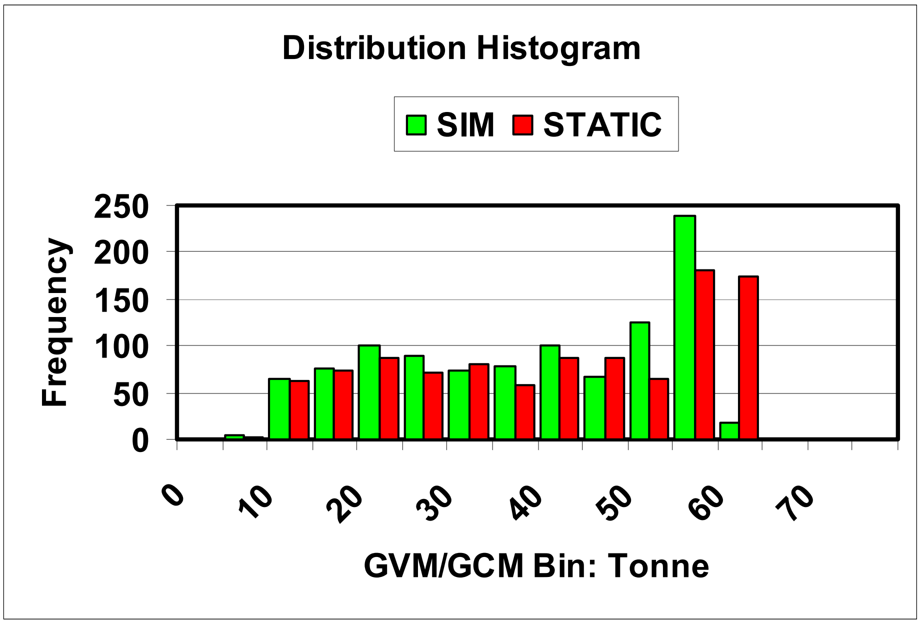

Figure 4: Distribution histogram of the GVM/GCM for the SIM & Static scales (n = 1 861) (Bin ranges in tonnes)

4.2 Comparison between scales (GVM/GCM)

In Figure 5 it can be seen that, based on paired data from 1 861 trucks for the SIM and Static scales and 1 501 trucks for the SIM and DAW 50 scales, there is a very good linear correlation (with $R^2 > 0.9$) between SIM data and both the Static and the DAW 50 data. In this example the SIM data are used as the independent variable and the data from the other two scales as the dependent variables, respectively. However, based on the statistical comparison (ANOVA), the null hypothesis (*H*o) (*H*o: population means are equal) is rejected and it is concluded that the population mean of the results obtained on the SIM scale is statistically different from the population means of those obtained on both the DAW 50 and Static scales. The SIM device underestimated the GVM/GCM by 6 to 7 per cent by comparison with the DAW 50 and Static devices at levels of significance of $\alpha = 1$, 5 and 10 per cent. This indicates that the SIM GVM/GCM data would have to be calibrated by an upward adjustment of the results in order to yield similar outcomes. However, it is believed that misalignment of the trucks and truck axles over the SIM, the condition of the tyres and, to a lesser extent, a possible calibration error with the SIM pads, were the main causes of this underestimation. Direct comparisons were also made between the results from the Multi - Deck Static and the DAW 50 scales, using the GVM/GCM paired data sets. This comparison shows a good linear and almost one-to one relationship between the paired results from 1 771 trucks (De Beer et al, 2004c). Furthermore, for these two scales, null hypothesis cannot be rejected and it is concluded that the population mean of the results from the Static scale is equal to the population mean of the results from the DAW 50 scale at levels of significance of $\alpha = 1$, 5 and 10 per cent (De Beer et al, 2004c). This implies that comparisons of the SIM data at the N3-TCC site with data obtained from the other two scales are based on a sound foundation.

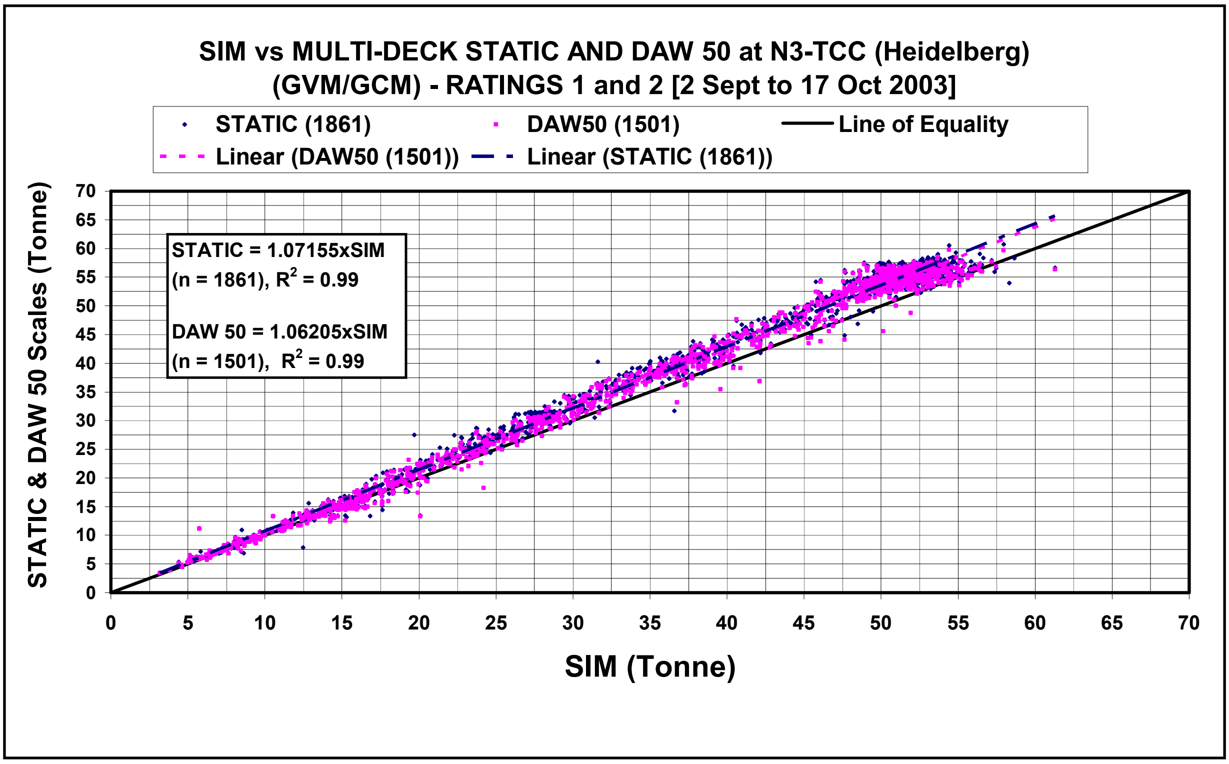

Figure 5: GVM/GCM from the SIM vs Multi-Deck Static and DAW 50 at N3-TCC

The relative accuracy between the scales, as well as the relative +/- prediction limits at different percentile values, is shown in Table A1 in Appendix A. As indicated above, the SIM values are approximately 6 to 7 per cent lower than the data from the DAW 50 and Static scales. See also Figure 5 in this regard. In the case of the Static/DAW 50 data, the relative accuracy is much higher (1.2 per cent) (See Table A1). The relative accuracy and relative prediction limits were obtained by the method described by Theyse and Muthen (2000). The +/- prediction limits indicate the boundaries within which a certain percentage of the individual data points from the population will lie, with a given probability. Table A1 indicates that the relative +/- prediction limits for GVM/GCM range from +/- 2 tonnes at the 80^{th} percentile (P80) to +/- 4.1 tonnes at the 99^{th} percentile (P99) for the SIM. Between the DAW 50 and the Static scales the limits are narrower: +/- 0.99 tonnes (P80) to +/- 2.0 tonnes (P99). Both the increased accuracy and the narrower limits between the results from the Static and DAW 50 scales are indicative of the proper calibration of these two scales on a relative basis. The results from these scales may therefore be used with confidence for comparison with the results from the SIM device.

5. STATISTICAL ANALYSIS: AXLE MASS WEIGHTS

Since the DAW 50 is a Weigh-In-Motion (WIM) device, at slow speeds (< 6 km/h) the individual axle mass weights are measured and the data are thus comparable with the (paired) SIM axle mass weight data. For the SIM measurements the axle mass weight is the sum of the mass weights of all the individual tyres weighed on that particular axle. With individual single axle mass weight data, relatively good linear comparisons were obtained for all the axles (i.e. Axles 1 to 8) studied here. The relative accuracies of the SIM vs the DAW 50 data are shown in Table A1 of Appendix A. The relative accuracies (per axle) vary between 0.3 per cent (Axle 1) to almost 20 per cent (Axle 8). However, the underestimation of the axle mass weights by more than approximately 10 per cent as measured on the SIM device appears to be limited to longer trucks (1:2:3 and 1:2:2:2), i.e from Axles 5 to 8. The relative +/- prediction limits are also shown in Table A1 and vary from +/- 0.6 tonnes (P80) to +/-2.0 tonnes (P99) for all the paired axle data sets studied. Both the lower accuracies and higher prediction limits are mainly associated with longer trucks and are therefore believed to originate from the alignment problem, where these trucks approached the SIM on a horizontal curve, thus partly missing the SIM measurement pads. Another factor may be the slight vertical ascending gradient of 0.9 per cent of the approach slab in front of the DAW 50 and SIM devices, influencing the results of the axle mass weights by the DAW 50 and the SIM device (De Beer et al, 2004c). However, the correlations are very linear and may therefore be adjusted with a single percentage factor per axle to yield comparable mass weight results (De Beer et al, 2004c).

6. STATISTICAL ANALYSIS: AXLE GROUP MASS WEIGHTS

As in the case of individual axles, comparisons were also made on the basis of paired axle group mass weights. In this case the SIM data were compared with data from both the DAW 50 and the Multi - Deck Static scales. The normal configuration of the Staic scale for axle groups is used (i.e Groups A, B, C and D). Most of the data for Axle Groups A (steering axles) and B (mainly drive axles) is linear and centred on the line of equality (relative accuracy 2 to 5 per cent), with some scatter. For Axle Groups C and D the correlations were also found to be linear, but the SIM results are approximately 10 per cent less than those measured on the other devices (De Beer et al, 2004c). The detailed statistical analysis indicated that the SIM axle group data would have to be adjusted upwards (as mentioned previously) for better comparison with the mass weight data from the Static and DAW 50 scales. The relative accuracy and the +/- prediction limits for all the axle groups (A, B, C and D) are shown in Table A2 of Appendix A. The poorest correlation was found to be between the results from the SIM and Static scales, with relative accuracies ranging from 2 per cent (Axle Group A) to 10 per cent (Axle Group D). In general, the relative accuracies between the DAW 50 and Static scales were better than those of the SIM device, the percentage differences ranging between 1 and 2 per cent.

The relative +/- prediction limits for the SIM, DAW 50 and Static scales range between approximately +/- 0.6 tonnes (P80) to +/- 3.5 tonnes (P99). Between the DAW 50 and the Static scales these limits range between approximately +/-0.6 tonnes (P80) to +/- 2.5 tonnes (P99), which are somewhat lower than those for the SIM device. The reasons for the higher prediction limits from the SIM data are the same as those mentioned earlier (alignment, approach etc) and typically occur with Axle Groups C and D (i.e. with longer trucks types 1:2:2:2 and 1:2:3).

7. REPEATABILITY AND REPRODUCIBILITY

Four (4) dedicated trucks were used to obtain an estimate of the precision of the SIM scale, albeit on very limited sample sizes. This was done by using four dedicated trucks with repeat runs over all three scales on different days. Precision is a general term for the variability between repeated tests. The two measures of precision are (i) repeatability (r) and (ii) Reproducibility (R). Repeatability (r) is typically used to compare in the results of tests carried out on the same day and Reproducibility (R) is used to compare the results of tests carried out on different days. The level of significance to determine r and R was 5 per cent (α = 5 per cent).

The measurements of the following trucks were included in the estimation:

- 1:1 Rigid truck: CSIR Deflectograph: Registration – KVJ 987 GP (GVM ~14 tonnes);
- 1:1 Rigid Truck loaded with concrete New Jersey barriers: Registration - KKL 659 GP (GVM ~15 tonnes);
- 1:2:3 Articulated Truck loaded with concrete New Jersey barriers: Registration - JHR 225 GP (GCM ~ 30 tonnes);
- 1:2:2:2 Articulated Truck loaded with concrete New Jersey barriers: Registration - DDL 156 GP (GCM ~ 50 tonnes);

The results of the mean (m), repeatability (r) and Reproducibility (R) of the GVMs/GCMs measured by the three different scales are summarized in Table 3. Based on this rather limited study, the r and R for the SIM scale are much higher than r and R for both the Static and DAW 50 scales. Depending on the truck type, and hence on its length or number of axles, the repeatability (r) of the SIM scale ranges from +/- 1.55 tonnes to +/- 4.02 tonnes. The Reproducibility (R) of the SIM measurements was found to range between +/- 1.41 tonnes to +/- 3.24 tonnes. These rather wide limits were however expected because of the nature the mass weight data sets (per tyre) obtained from the SIM scale. As discussed above, the mass weight data from the SIM is sensitive to factors such as alignment of the axles and axle groups over the SIM during measurement, quality of the tyre at the point of measurement, axle speed etc.

Measurements on the Static and DAW 50 scales seem to be more repeatable and reproducible than those on the SIM scale at a α = 5 per cent level of significance, with repeatability results (r) ranging from +/- 0.055 tonnes to +/- 0.108 tonnes for the Static scale and from +/- 0.269 tonnes to +/- 0.969 tonnes for the DAW 50 scale. The reproducibility results (R) range from +/- 0.177 tonnes to+/- 0.217 tonnes and from +/- 0.328 tonnes to +/- 0.854 tonnes for the Static and DAW 50 scales respectively. See Table 3.

The under-recording of the mean GVM/GCM results (m) by the SIM scale of the two longer trucks types 1:2:2:2 and 1:2:3, is also evident for reasons as discussed earlier (i.e. 6 to 7 per cent).

Table 3: Repeatability (r) and Reproducibility (R) for the dedicated trucks on the SIM, Static and DAW 50 scales (GVM/GCM) at α = 5 per cent

	Truck Identification and type			
STATISTICS	**DDJ 156 GP 1:2:2:2**	**JHR 225 GP 1:2:3**	**KKL 659 GP 1:1**	**KVJ 987 GP 1:1**
GVM/GCM (+/- Tonnes)				
Number of different measuring dates and sum of replicates (T)	**4 (T = 11)**	**7 (T = 23)**	**11 (T = 74)**	**4 (T = 27)**
Scale	**SIM**			
m	50.531	28.315	14.709	13.681
r	4.024	1.548	1.655	2.299
R	3.235	1.410	1.701	2.529
Scale	**STATIC**			
m	56.996	31.349	15.101	13.467
r	0.108	0.055	0.062	0.099
R	0.188	0.217	0.177	0.163
Scale	**DAW 50**			
m	56.456	30.274	14.880	13.125
r	0.969	0.773	0.269	0.830
R	0.854	0.772	0.328	0.873

However it is believed that a much larger number of samples (i.e. more replicate measurements) are needed to confirm these limits given above for the three scales. Further work is therefore suggested here.

8. SUMMARY AND CONCLUSIONS

- In this study the mass weight results from three different weighing devices (scales) at the N3-Traffic Control Centre near Heidelberg were statistically compared and the precision was also studied using repeatability (r) and Reproducibility (R). A total of 3 047 trucks (17 770) axles were measured at this site over a total period of 6 weeks with the new SIM device. A quality rating on the total data set was done and the data from a total of 2 297 trucks (12 830 axles) were finally rated as Good (2) to Very Good (1) data sets, which could be used in comparison with the other two scales on this test site.
- For comparison purposes, the GVM/GCM data from a total of 1 861 trucks (paired data) from the SIM and Static scales were compared, as well as the data from 1 501 trucks (paired data) on the SIM and DAW 50 WIM scales. In addition, the data from 1 771 trucks (paired data) were used to compare the DAW 50 and Static scales.
- In the case of axle groups, the number of trucks (paired data) used for comparison were 1 585 for both Axle Groups A and B and 1 229 and 818 for Axle Groups C and D, respectively.

- In the case of individual axles, the SIM axle data sets were compared only with those from the DAW 50. The total number of axles (paired data) used for comparison was 4 288 (Sum of Axles 1 to 8).
- The results (GVM/GCM, axle groups and single axles) from the SIM system correlated very linearly with those from the other two scales. However, the comparative data indicated that the SIM system underestimated the average GVM/GCM data by 6 to 7 per cent, axle group mass weights by 2 to 10 per cent and single axle mass weights by between 0.3 and 19 per cent at levels of significance of α = 1, 5 and 10 per cent. It is, however, believed that the underestimation mainly resulted from misalignment of truck axles, the quality of the tyres at the point of measurement and the curved and the non-level truck approach to the SIM device.
- Comparison between the data from the DAW 50 and the Multi – Deck Static scales indicated an almost exact linear relationship, with relative accuracies of between 1 and 1.5 per cent. Thus application of linear adjustments to the SIM axle mass weights, SIM axle group mass weights and to SIM GVMs/GCMs should result in data which would be highly comparable with the data from the DAW 50 and Multi – Deck Static scales.
- Based on relative prediction limits the SIM GVM/GCM data seem to suggest limits ranging from +/- 2.0 tonnes at the 80th percentile to +/- 4.1 tonnes at the 99th percentile. For the DAW 50 and Static scales these limits are lower (i.e. have higher precision), being +/- 0.99 tonnes at the 80th percentile and +/- 2.0 tonnes at the 99th percentile.
- For the mass weights of the axle groups the relative prediction limits of the SIM data are approximately +/- 0.6 tonnes at the 80th percentile and +/- 3.5 tonnes at the 99th percentile. For the axle groups the relative prediction limits of the DAW 50 and Static scales are approximately +/- 0.6 tonnes at the 80th percentile and +/- 2.5 tonnes at the 99th percentile, somewhat narrower compared to the SIM data.
- The mass weight data from single axles from the SIM device, by comparison with those from the DAW 50 scale, suggest prediction limits of +/- 0.6 tonnes at the 80th percentile and +/- 2.2 tonnes at the 99th percentile.
- Precision testing (albeit on a very limited sample sizes) of the DAW 50 data indicated relatively narrow limits of repeatability (r) (+/- 0.27 tonnes to +/- 0.97 tonnes) and Reproducibility (R) (+/- 0.33 tonnes to +/- 0.85 tonnes) at a α = 5 per cent level of significance.
- As for above, the data from the Static scale indicated also relatively narrow limits of repeatability (r) (+/- 1.06 tonnes to +/- 0.11 tonnes) and Reproducibility (R) (+/- 0.18 tonnes to +/- 0.27 tonnes) at a α = 5 per cent level of significance.
- However, the SIM data indicated relatively wide limits of repeatability (r) (+/- 1.6 tonnes to +/- 4.02 tonnes) and Reproducibility (R) (+/- 1.41 tonnes to +/- 3.24 tonnes) at α = 5 per cent level of significance, compared to the DAW 50 and Static scales.
- With relative accuracy and relative prediction limits established, it is concluded that, based on the results of this study (and provided the suggested adjustments are made), the SIM system can be used with confidence for the mass weight data, as well as for expanding the tyre-pavement contact stress data base at CSIR Transportek, for the purposes of improved mechanistic road pavement design and analyses.

9. RECOMMENDATIONS

It is recommended that:

- A factory check be done on the SIM scales (i.e. 4 pads), by applying external total loads/weights and recording the outputs. From this, the required adjustment factor may be confirmed, and if so, can be included as part of the SIM calibration process and protocols.
- For similar studies on other traffic control centres (or sites), a longer and flatter approach slab be constructed in order to avoid the alignment problem found with longer trucks, as was the case at the N3-TCC site. This would enable a larger amount of measurements to be rated as Very Good (VG) and Good (G) in a future measurement series at the N3-TCC.
- For more optimal use and linkages between data sets from various WIM scales, future studies be designed to facilitate the automatic linking of all data sets from the same truck on all the different scales, including the SIM.
- Finally, based on the rather favourable outcome of this study, the current available SIM data (or new data sets) be used (with the suggested adjustments on mass weight data) to further study the effects of real tyre-pavement contact stresses on the South African range of flexible pavements, with the aim of replacing assumptions of stress uniformity during the road pavement design process.

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APPENDIX A

ACCURACY AND PREDICTION LIMITS FOUND FOR THE DIFFERENT SCALES

TABLES A1 and A2

Table A1: Relative accuracy and prediction limits at different percentile values of the GVM/GCM

Mass Weights	Accuracy of Dependent Variable (%)	RELATIVE PREDICTION LIMITS AT DIFFERENT PERCENTILE VALUES (+/- Tonne)				Dependent (Y) Variable	Independent (X) Variable
		P80	P90	P95	P99		
GVM/GCM SIM and DAW 50	-6.818	1.896	2.437	2.907	3.834	SIM	DAW 50
	6.205*	2.015	2.590	3.090	4.075	DAW 50	SIM
GVM/GCM SIM and Static	7.155	2.026	2.605	3.107	4.099	STATIC	SIM
	-6.818	1.890	2.429	2.898	3.822	SIM	STATIC
GVM/GCM Static and DAW 50	1.252	0.999	1.285	1.533	2.022	STATIC	DAW 50
	-1.269	0.987	1.269	1.513	1.996	DAW 50	STATIC
Axle No and number of samples	**Accuracy of Dependent Variable (%)**	**RELATIVE PREDICTION LIMITS AT DIFFERENT PERCENTILE VALUES (+/- Tonne)**				**Dependent (Y) Variable**	**Independent (X) Variable**
		P80	**P90**	**P95**	**P99**		
AXLE 1 (n = 1 666)	-0.265	0.577	0.741	0.884	1.166	SIM	DAW 50
	-0.336	0.576	0.741	0.884	1.166	DAW 50	SIM
AXLE 2 (n = 629)	-1.545	0.722	0.928	1.107	1.461	SIM	DAW 50
	1.044	0.732	0.940	1.122	1.480	DAW 50	SIM
AXLE 3 (n = 454)	-5.726	0.678	0.871	1.039	1.370	SIM	DAW 50
	5.454	0.716	0.921	1.098	1.449	DAW 50	SIM
AXLE 4 (434)	0.030	0.752	0.967	1.153	1.521	SIM	DAW 50
	-0.711	0.749	0.963	1.149	1.516	DAW 50	SIM
AXLE 5 (n = 416)	-12.230	0.668	0.859	1.025	1.351	SIM	DAW 50
	13.193	0.759	0.975	1.164	1.535	DAW 50	SIM
AXLE 6 (n = 401)	-8.220	1.004	1.290	1.539	2.030	SIM	DAW 50
	7.320	1.085	1.395	1.664	2.195	DAW 50	SIM
AXLE 7 (n = 270)	-16.069	0.931	1.196	1.427	1.882	SIM	DAW 50
	17.635	1.102	1.416	1.689	2.228	DAW 50	SIM
AXLE 8 (n= 18)	-17.919	0.800	1.045	1.268	1.748	SIM	DAW 50
	20.574	0.969	1.266	1.537	2.118	DAW 50	SIM

* Relative to Independent variable

Table A2: Relative accuracy and prediction limits at different percentile values of the Axle Group mass weights

Axle Groups and No of samples	Accuracy of Dependent Variable (%)*	RELATIVE PREDICTION LIMITS AT DIFFERENT PERCENTILE VALUES (+/- Tonne)				Dependent (Y) Variable	Independent (X) Variable
		P80	P90	P95	P99		
Group A (n = 1 585)	-0.780	0.834	1.073	1.280	1.688	SIM	DAW 50
	-0.474	0.836	1.074	1.281	1.690	DAW 50	SIM
	2.002	0.638	0.820	0.979	1.291	STATIC	SIM
	-2.647	0.624	0.802	0.956	1.261	SIM	STATIC
	1.917	0.571	0.734	0.876	1.156	STATIC	DAW 50
	-2.430	0.559	0.719	0.857	1.131	DAW 50	STATIC
Group B (n = 1 585)	-4.059	1.039	1.335	1.593	2.101	SIM	DAW 50
	3.809	1.251	1.389	1.657	2.185	DAW 50	SIM
	4.703	1.166	1.499	1.789	2.359	STATIC	SIM
	-4.934	1.111	1.429	1.704	2.248	SIM	STATIC
	0.815	0.662	0.850	1.014	1.338	STATIC	DAW 50
	-0.956	0.656	0.843	1.005	1.326	DAW 50	STATIC
Group C (n = 1 229)	-8.088	1.274	1.638	1.954	2.577	SIM	DAW 50
	8.270	1.383	1.778	2.121	2.797	DAW 50	SIM
	9.986	1.461	1.878	2.241	2.955	STATIC	SIM
	-9.558	1.325	1.703	2.032	2.680	SIM	STATIC
	1.363	1.390	1.787	2.131	2.811	STATIC	DAW 50
	-0.956	0.656	0.843	1.005	1.326	DAW 50	STATIC
Group D (n = 818)	-10.468	1.580	2.031	2.423	3.196	SIM	DAW 50
	10.672	1.757	2.258	2.694	3.553	DAW 50	SIM
	12.032	1.591	2.045	2.440	3.218	STATIC	SIM
	-9.558	1.325	1.704	2.032	2.681	SIM	STATIC
	0.913	1.234	1.586	1.893	2.496	STATIC	DAW 50
	-1.342	1.220	1.568	1.871	2.468	DAW 50	STATIC

* Relative to Independent variable