

MEASUREMENT TECHNOLOGY FOR A CALIBRATING VEHICLE FOR MULTIPLE SENSOR WEIGH-IN-MOTION SYSTEMS

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ABSTRACT

The 'Dutch Ministry of Transport, Public Works and Water Management' requested for an instrumented vehicle to calibrate their Multiple Sensor Weigh-In-Motion (MSWIM) system that is under development for automatic enforcement of axle loads and vehicle weights. The requirements for the calibration vehicle are: 1) static wheel loads between 25 and 75 kN; 2) vehicle speeds between 50 and 100 km/h, and; 3) an accuracy of the measurements of 95% at the requested static wheel loads. This calibration vehicle has been built by TNO and the Dutch organisation KALIBRA International B.V. KALIBRA delivered the DAF 95XF530 6x4 tractor and the specially built Nooteboom five axle semi-trailer. The vehicle was planned to be built for calibration of static weigh bridges, and has been redesigned for the purpose of calibrating MSWIM systems. TNO has developed and built the measuring system and software. The axle load can vary from 30 to 150 kN with an accuracy of 50 daN by means of: 1) the mass of the unloaded semi-trailer; 2) a payload of maximal 44 metal blocs of 1000 kg each; and 3) lifting axles. The first axle on the semi-trailer has been instrumented with strain gauges and accelerometers. The data is collected with a sample rate of 8 kHz. The system clock is synchronised with an accurate GPS time trigger. The same GPS time trigger is used for synchronisation with the MSWIM system. The dynamic wheel loads are calculated using data from the strain gauges and from accelerometers measuring wheel accelerations. The calibration measurement is controlled by a computer in the cabin via a wireless link. After each run the calculated dynamic wheel load data is transferred to the MSWIM system and the WIM data of each WIM sensor (time and load) is compared with the time history of the wheel load from the vehicle. The dynamic axle load measurement system has been built into the vehicle and has been calibrated. This paper presents the basis of the developed system and the test results. The first calibration runs of the MSWIM system took place in November and December 2003.

INTRODUCTION

The Road and Hydraulic Engineering Institute of the Dutch Ministry of Transport, Public Works and Water Management is testing a so called Multiple Sensor Weigh-In-Motion (MSWIM) system for measuring the dynamic wheel loads of heavy vehicles 'in-traffic'. From these dynamic loads the static axle loads and gross vehicle weight can be estimated. The goal of the project is to build a MSWIM system that is accurate and reliable enough to be used as enforcement equipment. For the initial verification of the individual WIM sensors, a calibrating instrument was needed. This paper is linked to the paper of Van Loo, ea. [1], which describes the political issue, the overall WIM-enforcement project and the implementation of the calibrating vehicle. The requirements for that dedicated instrument/ vehicle are: 1) static wheel loads between 25 and 75 kN; 2) vehicle speeds between 50 and 100 km/h; and 3) an accuracy of the measurements of 95% at the requested static wheel loads [2]. The Dutch calibrating organisation KALIBRA International B.V. uses a specially built vehicle for the calibration of 'Static Weigh Bridge', see Figure 1. This vehicle is used to house the WIM calibrating system. This project is reported in [3].

THE VEHICLE

The calibrating vehicle is a tractor semi-trailer combination with a maximum total vehicle weight of 78 metric tonnes. The tractor is a DAF 95XF530 (6x4) and the five-axle semi-trailer has been made by Nootboom. The first axle of the semi-trailer is fixed and the others are steered hydraulically. All axles except the third axle are liftable. The first axle is the 'instrumented' axle for measuring the dynamic wheel loads. The total vehicle weight is derived from the unloaded vehicle mass and from 44 stainless steel blocs of 1000 kg each. In combination with the liftable axles any static load on the first axle from 30 to 150 kN can be arranged within an accuracy of 50 daN. Lifting of the first axle is used to zero the load sensors.



Figure 1. DAF 95XF530 (6x4) tractor and five axle Nootboom semi-trailer for calibration.

The load sensors

The dynamic axle load is measured by strain gauges. The SAF¹ axle is hollow with an outside diameter of 127 mm and an inside diameter of 77 mm. The part of the axle between the ground plate of the braking system and the fixation points for the hydraulic suspension system at each end of the axle is used to measure the wheel loads. This part is small, but wide enough to mount the sensor.

The bending stress at the upper and lower part of the axle can not be used to quantify the vertical wheel load, because the bending moment is not only related to the wheel load itself, but also to the lateral position of the wheel load, which may vary on uneven roads by up to 25%. Also lateral wheel forces will contribute to the bending moment. The shear stress along the neutral axis of the axle is not related to the lateral position of the wheel load and lateral wheel forces and therefore is an accurate representation of the vertical wheel load on each side of the axle. But the problem is that this strain signal is very weak.

TNO developed a mechanical strain amplifier, comprising a 'bar' with a thin sensor section in the middle. The stiffness of the middle section is an order-of-magnitude smaller than the adjacent supporting section, see Figure 2.

The strain gauges are fixed to the middle section where the stresses are concentrated. Two of these elements are configured to form a full strain gauge bridge in a 90° cross (see Figure 3). The cross is placed as one element on the axle between the hub and the connection point to the suspension system, see Figure 5. The centre of the cross is placed exactly on the neutral axis of the axle. Special fixation elements are used to make it possible to (de)mount the set when needed, see Figures 4 and 5. The sensor set is covered with a stainless steel box for protection against water, dirt etc.

¹ SAF; Otto Sauer Achsenfabrik Keilberg KG, Germany, <http://www.saf-achsen.de/>

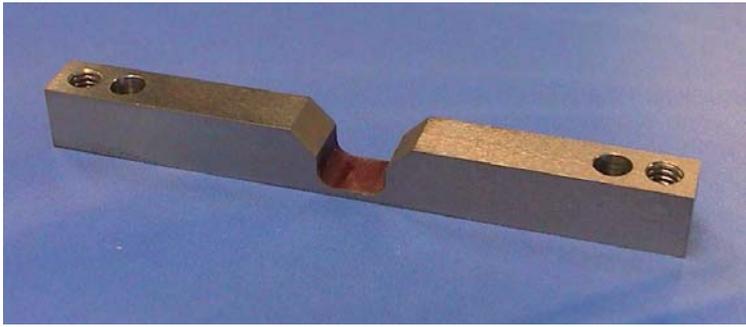


Figure 2. Mechanical stress/ strain amplifier.

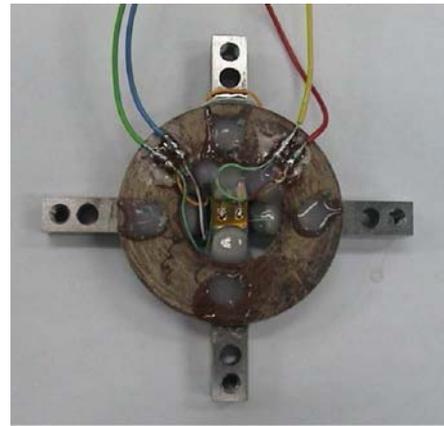


Figure 3. Set of mechanical strain amplifiers in a full bridge set-up.



Figure 4. Mounting points for the set on the axle.



Figure 5. Location of the set on the axle.

$$L + m \cdot z_c - V = 0$$

With:

- L = wheel load;
- m = wheel mass outboard of the sensor;
- z_c = vertical acceleration;
- V = measured shear force in the strain gauge bridge.

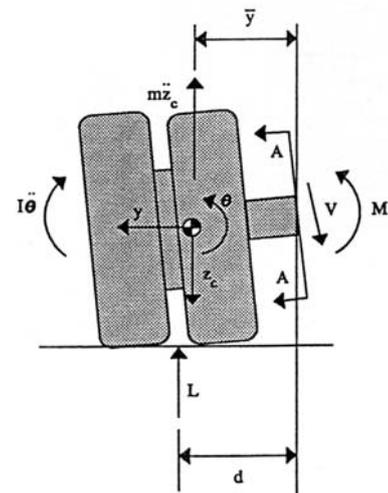


Figure 6. Left axle side.

Correction for inertia forces

The requested level of accuracy of the measuring system is so high that it was necessary to correct the measured data from the strain gauge for the influence of the acceleration-induced inertia forces of the wheels, the hub and the braking system by accelerometers mounted on the axle, see Figure 6.

Data acquisition system and data processing

The data-acquisition system is based on the National Instruments PXI-1010 hardware and LABVIEW software. The signals of the two strain-gauge full bridge sets and the two accelerometers are recorded using the same sample frequency as used by the MSWIM system itself (8196 Hz). The time signal is derived from the GPS time generator.

Before the actual calibration experiments the first axle is lifted from the ground and data are recorded, defining the zero. The measured data from the strain-gauge sensors during the calibration run are corrected in real-time for zero and for wheel inertia using the data from the accelerometers. The calibration measurement is controlled by a laptop computer in the cabin via a wireless link. After each run the calculated dynamic wheel load data is transferred to the MSWIM system, and the MSWIM data of each WIM sensor (time and load) is compared with the time history of the wheel load from the vehicle.

Time stamping

The wheel load data from the calibration vehicle and the MSWIM system are compared. A trigger point is needed for an accurate comparison of the data generated by two stand-alone systems. Another option is to synchronise the time base of both data series.

In both data acquisition systems the data is sampled with 8196 Hz. The contact time between the individual WIM-sensor and the passing tyre is a function of the length of the wheel-print (approx. 20 cm) and vehicle speed. With a vehicle speed of 105 km/h (30 m/s) this equals a time frame of 7 ms during which about 56 wheel load samples will be recorded.

We considered using the PTB DCF77 (Braunschweig) atom clock pulse for synchronisation, being very accurate for long time periods with 10^{-13} per week. But the time stamp in each measuring system may vary from 5 to 25 ms because of the fact that the time signal is transported using a radio signal of 77.5 kHz. This variation of 20 ms makes this PTB DCF77 time signal inaccurate and unacceptable.

A more accurate time signal is generated by the GPS world clock (GPS-UTC). The accuracy of this signal is 250 ns for vehicle speeds up to 1440 km/h when the same Time and Frequency Generator Datum ET6000 is used based on contact with six satellites [4]. It was decided that both WIM and vehicle data acquisition systems will use the same Datum ET6000 system.



Figure 7. Hydraulic cylinders underneath the first axle.



Figure 8. Levelled semi-trailer in the Lab for calibrating the measurement system.

Static calibration of the wheel load measuring system

The vehicle is placed in a levelled position with the wheels of the first axle (measuring axle) on two hydraulic cylinders, see Figures 7 and 8. A calibrated load cell between the wheels and the hydraulic cylinder is used to measure the actual wheel loads. Both wheels (left & right) of the first axle are located on a steel plateau. A ball-joint connection between the plateau and the load cell is used to exclude other loads then the wheel load ‘in-line’ with the load cell, see Figure 9.

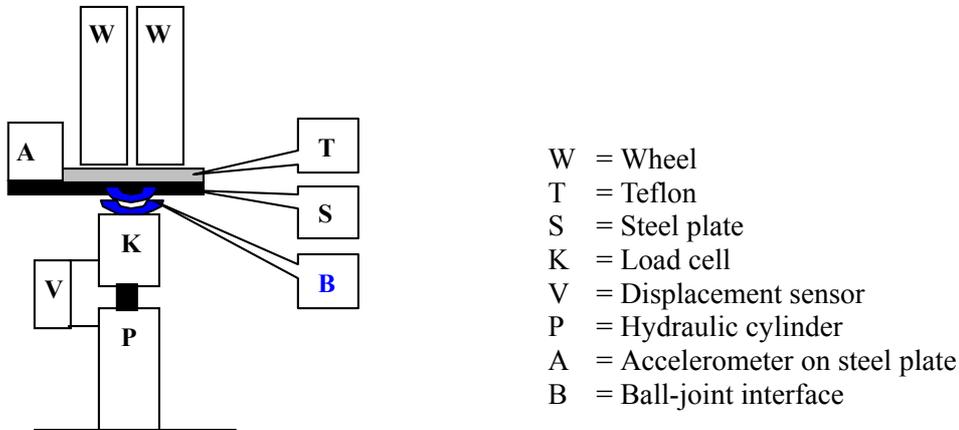


Figure 9. Hydraulic actuator, load cell and steel plate underneath the wheel set.

The static wheel load from 15 to 75 kN is introduced by the steel blocs and/ or by lifting axles ‘2’, ‘4’ and ‘5’. For these wheel loads the measured load from the calibrated load cell is used to obtain the gain factor and offset for the data acquisition system in the semi-trailer. The gain was very constant over the wheel loads from 15 to 75 kN, see Figure 10 and Table 1.

Several static experiments have been executed to check the stability of the system with good results.

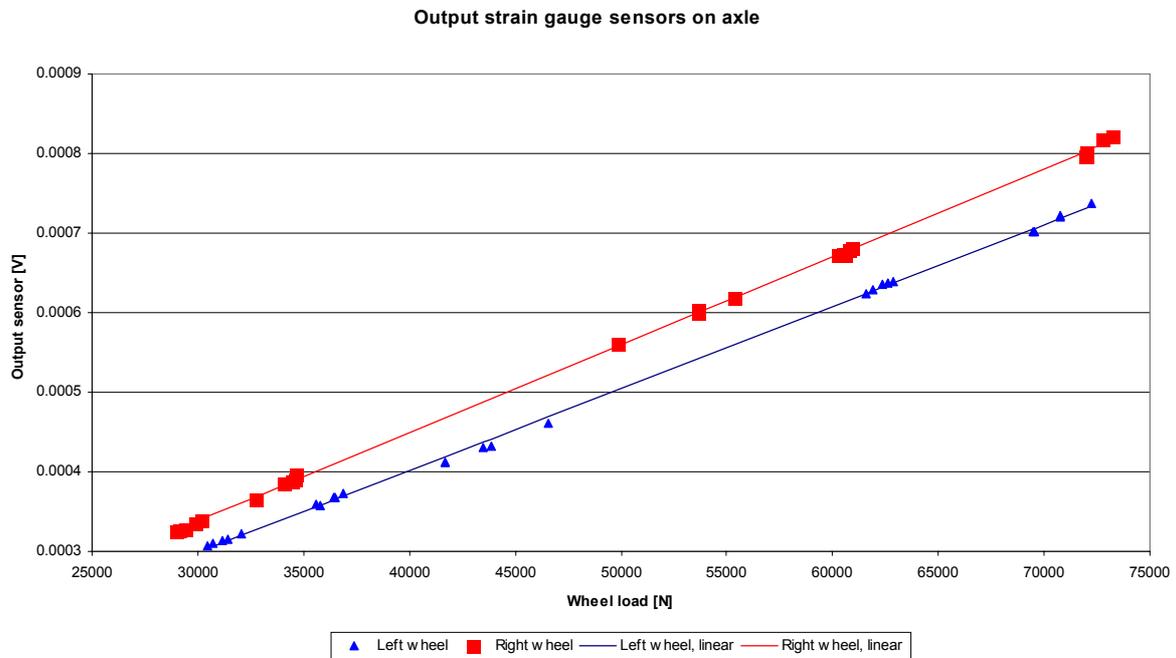


Figure 10. Gain factor from strain gauge signal [V] to wheel load [N].

Table 1. Static calibration factors of the strain gauges.

Location	Gain [10^{-12} V/N]
Left	9710.39
Right	9047.65

Dynamic calibration of the wheel load measuring system

The dynamic calibration of the wheel load measuring system has been executed on the same test bench as used for the static calibration. With three nominal static wheel loads of 38, 50 and 60 kN a vertical sinusoidal sweep excitation is introduced by the hydraulic cylinders with an amplitude of 1.5 mm, and a frequency of 1.0 up to 13.5 Hz in 240 seconds. The left and right wheels were excited both in phase and anti phase. The complete system, including the contribution from the accelerometers on the axle to correct for the inertia of the wheels is taken into account during this dynamic calibration.

Accelerometers were mounted on the steel plateau to correct the measured load from the load cells for the inertia of the steel plate.

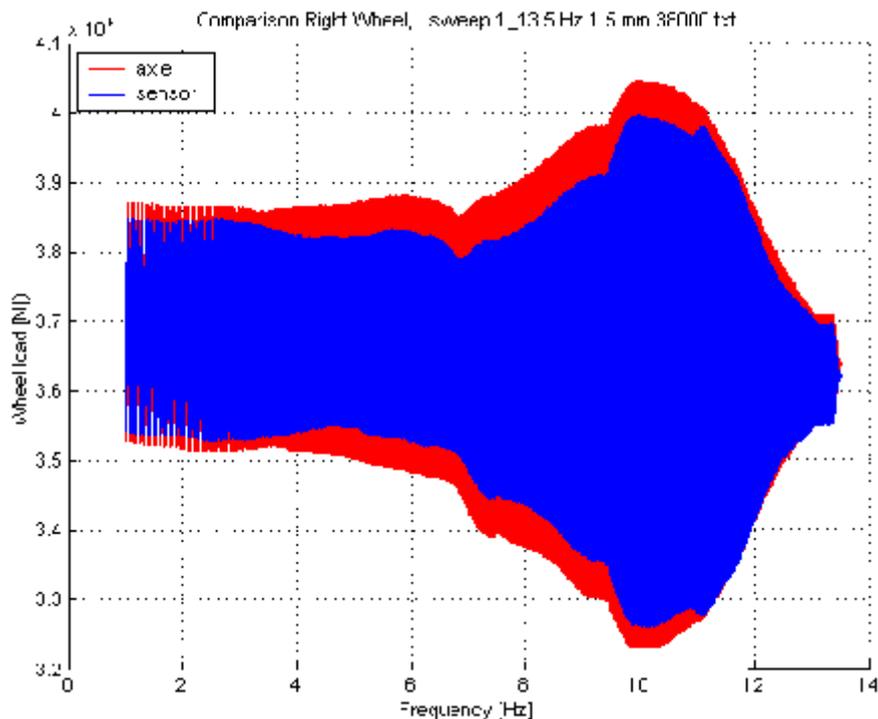


Figure 11. Right wheel, sinusoidal sinus sweep at 38 kN left and right wheel in phase.

An example of the corrected data of the load measuring system underneath the wheels and the corrected data from the axle sensors are plotted in Figure 11. The data is analysed for uncertainty factors through the bandwidth of 1.0 to 13.5 Hz.

Accuracy of the system according to the EA-4/02

The total accuracy of the measuring system was derived from the contribution of each and every used element in the calibration, according to the EA-4/02 [5].

The deviation in the measured load and the 'real' load is:

$$\Delta F = F_i - F_d + \delta F_{d,dev} + \delta F_{d,unc} + \delta F_{d,repr} + \delta F_{d,drift} + \delta F_{d,temp}$$

with:

- ΔF deviation in reading value at the measuring system (indicator);
- F_i load, measured with the measuring system (indicator);
- F_d load, measured with the calibrated load cell;
- $\delta F_{d,dev}$ deviation of the load cell mentioned in the certificate;
- $\delta F_{d,unc}$ deviation in the uncertainty of the load cell according to the certificate;
- $\delta F_{d,repro}$ deviation from the reproducibility;
- $\delta F_{d,drift}$ deviation from the drift of the system;
- $\delta F_{d,temp}$ deviation from the temperature drift of the system.

The standard uncertainty 'u' of the deviation in ΔF is derived from the uncertainty in each element. Table 2 shows the uncertainty participation of the elements.

Table 2. Uncertainty participation of the elements at 38 kN.

Parameter	Standard uncertainty [N]	Sensitivity	Uncertainty participation [N]
F_i	$3 / \sqrt{12}$	1	0.87
F_d	$3 / \sqrt{12}$	1	0.87
$\delta F_{d,dev,(right)}$	$0.8 \cdot 10^{-2} \cdot F / \sqrt{12}$	1	$0.23 \cdot 10^{-2} \cdot F$
$\delta F_{d,dev,(left)}$	$0.9 \cdot 10^{-2} \cdot F / \sqrt{12}$	1	$0.26 \cdot 10^{-2} \cdot F$
$\delta F_{d,unc}$	$0.25 \cdot 10^{-2} \cdot F / 2$	1	$0.125 \cdot 10^{-2} \cdot F$
$\delta F_{d,repro}$	$R \cdot 10^{-2} \cdot F / 2$	1	$0.5 \cdot R \cdot 10^{-2} \cdot F$
$\delta F_{d,drift}$	$(62.5 - (-62.5)) / \sqrt{12}$	1	36.1
$\delta F_{d,temp}$	NIHIL	1	0

According to the certificates the deviation of the left load cell ' $\delta F_{d,dev,(left)}$ ' differs from the deviation of right load cell ' $\delta F_{d,dev,(right)}$ '.

Deviation from the reproducibility ' $\delta F_{d,repro}$ ' was derived from the dynamic measurements on the test bench.

Deviation from the drift of the system ' $\delta F_{d,drift}$ ' was derived from a 24-hour static load to the system.

The total uncertainty 'U' is:

$$U = 2 \cdot u$$

$$U_{38,left} = 2 \cdot \sqrt{[(3/\sqrt{12})^2 + (3/\sqrt{12})^2 + (0.9 \cdot 10^{-2} F / \sqrt{12})^2 + (0.25 \cdot 10^{-2} F / 2)^2 + (R \cdot 10^{-2} F / 2)^2 + ((125/\sqrt{12})^2]}$$

From the dynamic test $R_{left,38} = 2.05$, and $R_{right,38} = 2.16$

$$U_{38,left} = 2.20\%$$

$$U_{38,right} = 2.34\%$$

The maximum standard deviation from the sinus sweep test at the lowest and highest value for the wheel loads (25 and 75 kN) were not measured but estimated from the maximum uncertainty at each of the measured wheel loads on each side, see Figure 12.

The calculation of the uncertainty was executed for all the frequency sweeps (phase and counter phase) and wheel loads of 38, 50 and 60 kN, at the left and right wheel (see Table 3) and for the wheel loads 25 and 75 kN (see Table 4).

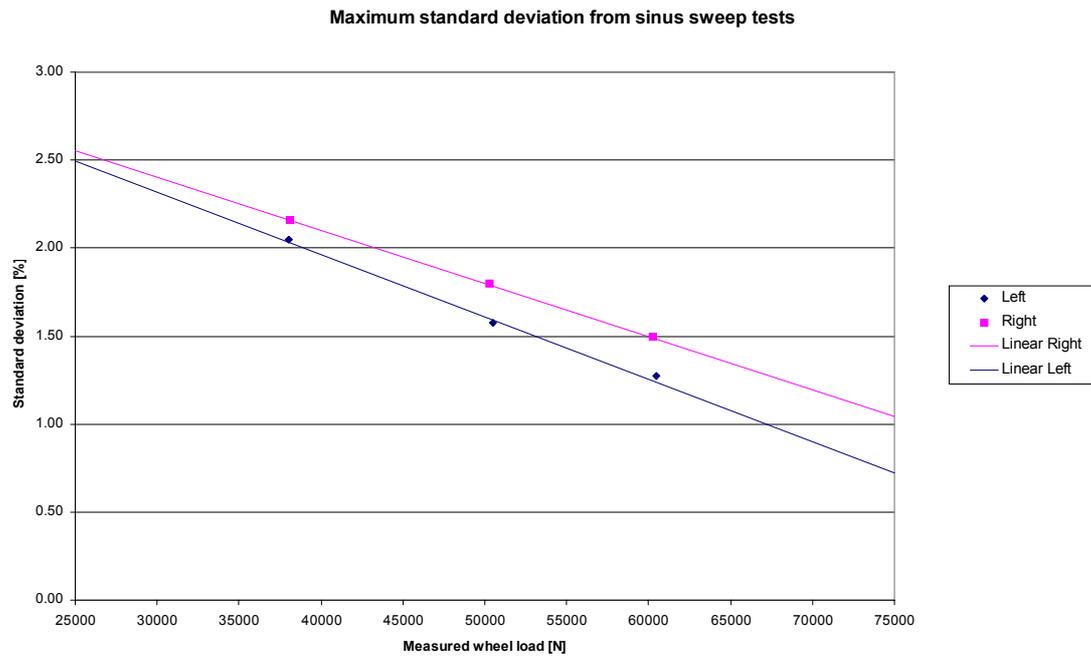


Figure 12. Standard deviation from the sinus sweep test, estimated at wheel loads 25 and 75 kN.

Table 3. Total maximum uncertainty at the three measured wheel loads 38, 50 an 60 kN, phase and counter phase, left and right.

Total uncertainty	Total maximum uncertainty [%]
38 kN, left wheel	2.20
38 kN, right wheel	2.34
50 kN, left wheel	2.24
50 kN, right wheel	2.49
60 kN, left wheel	2.15
60 kN, right wheel	2.02

Table 4. Total maximum estimated uncertainty at 25 and 75 kN, left and right.

Total uncertainty	Total maximum uncertainty [%]
25 kN, left wheel	4.49
25 kN, right wheel	4.14
75 kN, left wheel	1.58
75 kN, right wheel	1.68

The uncertainty at all wheel loads between 25 kN and 75 kN is smaller then the requested 5%.

CONCLUSION

The Road and Hydraulic Engineering Institute of the Dutch Ministry of Transport, Public Works and Water Management requested a dedicated calibration vehicle for their MSWIM-Hand enforcement system with: 1) static wheel loads between 25 and 75 kN; 2) vehicle speeds between 50 and 100 km/h; and 3) an accuracy of the measurements of 95% at the requested static wheel loads.

TNO developed special load sensors based on a full strain-gauge bridge for each side of the first axle of the semi-trailer. The load is corrected for the inertia of the wheels, braking system and hub. The time signal is based on the GPS world time with an accuracy of 250 ns and this time signal is equal for both WIM and vehicle data-acquisitions systems. The measuring system has been calibrated both statically and dynamically on a test bench.

The accuracy at all wheel loads between 25 and 75 kN is better than the requested 95%.

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