# VEHICLE FOR DYNAMIC CALIBRATION OF A MULTIPLE SENSOR WEIGH-IN-MOTION SYSTEM

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## ABSTRACT

For the Road and Hydraulic Engineering Institute (DWW) of the Dutch Ministry of Transport, Public Works and Water Management an instrumented vehicle has been built. This vehicle will be used for the dynamic calibration of Multiple Sensor Weigh-in-Motion systems and for the extensive performance test necessary for the acceptance of WIM-systems for automatic enforcement. The vehicle was built by a consortium led by Kalibra International BV with participation of TNO for the measurement technology and Nooteboom for the construction of the custom-built trailer. The vehicle consists of a three-axle tractor with a five-axle trailer of which one axle is instrumented, four axles are steerable and four axles are liftable. The costs for the WIM-related measurement equipment were approximately Euro 300.000,--.

The key specifications of the vehicle require that it should be able to measure axle loads from 5 to 15 tonnes at speeds up to 100 km/h in various axle configurations with an inaccuracy of less than 5%. The synchronisation between the instrumented vehicle and the WIM-system is done by using the exact time signal from GPS receivers. The measuring principle is based on strain gauges on the axle to measure the force of the trailer on that axle and accelerometers to measure the acceleration of the wheels to compensate for the movement of the wheels. The (static and dynamic) calibration of the vehicle was done by TNO (Hoogvelt, 2004). A calibration procedure has been devised consisting of several runs at various speeds with various axle loads. Unfortunately the WIM-Hand test-site is not operational yet so the validation of the measurements from the instrumented vehicle has not been performed.

**Keywords**: Instrumented Vehicle, Multiple Sensor, Weigh-in-Motion, Dynamic Calibration

## BACKGROUND

### Introduction

(Inter)national goods transportation by road is an important part of the Dutch economy; 173,000 trucks transport 600 million tonnes annually, [CBS, 2000]. Truck traffic in particular is burdening the infrastructure. The number and the loads of (axles of) trucks are the major determinant for the degree of maintenance, as there is a progressive (4th order) relationship between an axle load and the damage that this axle load causes to the road surface. A disproportionate large percentage of the damage to the infrastructure is caused by trucks with axle loads higher than the legal maximums. The direct costs for additional asphalt maintenance are roughly estimated at around Euro 17 million per annum for Dutch highways alone. This is excluding the costs as a result of additional hindrance to traffic (including traffic jams) caused by road works. Moreover, the policy of the Ministry of Transport, Public Works and Water Management is also aimed at stimulating fair competition between companies. Finally, overloading of one or more axles of a truck or the whole vehicle is also likely to have a negative effect on traffic safety.

To reduce the negative effects of overloading, the Directorate General Goods Transportation of the Dutch Ministry of Transport, Public Works and Water Management has started the project 'Overloading'. As part of this project the Road and Hydraulic Engineering Division (DWW) of the Ministry of Transport is working on two projects involving Weigh-in-Motion - WIM-NL and WIM-Hand. The WIM-NL project concerns the installation of six WIM+ Video-systems in the Netherlands [Saan, 2002]. The systems are used by enforcement agencies as a tool for pre-selection and pro-active controls. As static (stationary) weighing remains necessary, these methods of enforcement are extremely labour-intensive. Therefore, in parallel, the

WIM-Hand project was started. WIM-Hand stands for Weigh-In-Motion for automatic enforcement or, in Dutch, 'Handhaving'. This project investigates whether existing technology can be used for building an axle load measuring system that can be employed for automatic enforcement of overloading by heavy goods vehicles. Automatic enforcement means that a citation will be directly based on the measurement of the WIM-system.

## WIM-hand project

As a part of the WIM-Hand project a multi-sensor WIM test site has been built at the A12/A50 highway near Arnhem in the East of The Netherlands. The choice for the multi-sensor approach and the design of the sensor array was based on [Gillespie, 1996], [Dolcemascolo, 1998], [Cebon, 1999], [WAVE, 2001] and others. The test site consists of sixteen rows of sensors, each row consisting of four Kistler Lineas Piezo Quartz sensors [Kunz, 1999]. The length of each of the Kistler sensors is 1.0 meter, the spacing between each row of sensors is 1.5 meters, see figure 1. A full description of the design and installation of the test site can be found in [van Loo, 2001]. The system measures the wheel loads of all passing vehicles and stores the measured data from each sensor per vehicle in a database. Along with the measured data a number of video images of the vehicle is stored as well.

The measurement part of a WIM-system consists of the combination of the WIM-sensors and the surrounding pavement. As a result a WIM-system can only be calibrated when the sensors are installed in the road pavement. The basic idea of a multiple sensor WIM-systems is that by taking sufficient samples of the dynamic axle loads of the passing trucks the static axle loads can be calculated. The accuracy of most calculation algorithms is sensitive to the measurement error in the sampled axle load, except the neural network technique [Gonzalez, 2003]. That is why it is important that each sensor measures the exact value of the dynamic axle load the moment the axle passes over that sensor. This can be achieved if each individual sensor is dynamically calibrated. Dynamic calibration means that the sensor will be calibrated to the dynamic force measured by the measurement axle of the instrumented vehicle the moment it passes the sensor. As part of the WIM-Hand project an instrumented vehicle has been built to perform the dynamic calibration of the sensors of the WIM-Hand test site.
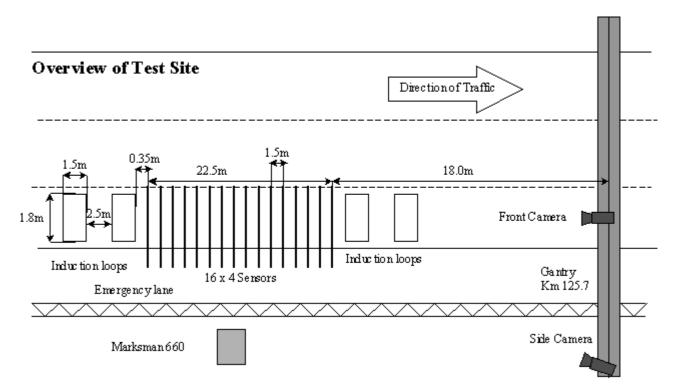


Figure 1. The WIM-hand test system.

**DESIGN OF THE VEHICLE**

During the last decades several instrumented vehicles have been built and used for calibration and testing of WIM-systems. For example the vehicles from the Transport Road Research Laboratory in the UK [Cebon, 1999], the National Research Council of Canada [WAVE, 2001] and the Technical Research Centre of Finland [Hutala, 1998]. However these vehicles are either based on outdated computer technology or not available for long periods of time in The Netherlands. That is why the possibilities were investigated to build a WIM-calibration vehicle in The Netherlands. Initially the possibilities for an extremely accurate instrumented vehicle were investigated with an inaccuracy of 2%. The advantage of such a vehicle is that the calibration can be carried out in one run. However, the investigation showed that the total cost for building the instrumented vehicle was estimated at around EURO 1 million with a turnaround time for construction of about 18 months, [Kuiper, 2000]. Therefore, it was decided to build a 'less' accurate vehicle with a maximum inaccuracy of 5% and perform the calibration over a number of runs.

The dynamic calibration of a WIM-system can be done in several ways: at a low speed with standard trucks or at a high speed with an instrumented vehicle. In the case of low speed calibration it is assumed that the dynamic part of the axle loads is negligible. Then the WIM-system can be calibrated to the axle loads that are measured when the vehicle is static. However, when the operational range of the WIM-system is tested at considerably higher speeds with such a standard truck, then the systems is in effect not calibrated for this operational range. Since the speeds at the test site vary around 80 km/h high speed calibration is preferred.

## Vehicle specifications

The key functional specifications for the instrumented vehicle for the WIM-Hand system include:
- The vehicle has to measure and store the dynamic forces that are exercised by the measurement axle on the WIM-system;
- The vehicle has to synchronise its measurements (in time) with the individual measurements of the WIM-system;
- The sample frequency of the measurement systems should be more than 8 kHz to be able to synchronise with the WIM-Hand system;
- The vehicle has to have a 'quiet' dynamic behaviour in order to minimise the dynamic component of load of the measurement axle;
- The vehicle has to be able to measure at speeds from 10 to 100 km/h;
- The vehicle has to be able to measure with axle loads from 5 to 15 tonnes;
- The inaccuracy of the measurements of the vehicle should be 5% or less over the entire measurement range;
- The calibration of the vehicle has to be traceable to international standards and approved by the national metric institute. The calibration procedure will be an integral part of the certification for future WIM-systems for automatic enforcement.

## Company requirements

For the selection of possible companies capable of building an instrumented vehicle and especially carrying out of the dynamic calibrations, the following criteria have been used:
- The company must be authorised by the Dutch Metric Institute (NMI) for the calibration of automatic weighing equipment. This company authorisation is required for the acceptation of the test results and approval of WIM-systems for automatic enforcement;
- The company has to have an ISO/IEC 17025 accreditation for the static calibration of weighing equipment of up to 50 tonnes. This is a registration of competence and quality assurance for the carrying out of calibrations in general;
- The company has to be able to perform the calibration independently. The calibration should be independent of the manufacturer of the sensors, the type of sensors, the set up of the system and the calculation algorithms that are used;
- The company has to have a vehicle that is used for calibration only. The WIM calibration equipment will be installed on this vehicle. It is very sensitive equipment that needs special care, even when the vehicle is not used for dynamic calibration;

- The company must be able to perform future re-calibrations and be available for additional testing on a regular basis in order to monitor the time stability of the system over a period of five years.

The only two companies in The Netherlands that were qualified were the NMI and Kalibra International B.V. However, the NMI indicated that it would outsource the calibration of WIM-systems to Kalibra. During the first discussions with Kalibra it became clear that the company already had plans for building a new tractor-trailer combination to be used for the calibration of static weighbridges. With relative small changes this vehicle could be made suitable for high-speed dynamic calibration of WIM-systems. For the DWW this would mean a cost saving of approximately Euro 600.000,- because it would no longer be necessary to build a new vehicle only for WIM. For Kalibra it would mean an additional application for their new vehicle and a competitive advantage in the future market for dynamic calibration of WIM-systems. In other words a 'Win-Win' situation.

## BUILDING OF THE VEHICLE

### Project organisation
The project was divided into two parts - the building of the vehicle and the execution of the measurements. The vehicle had to be ready within one year. After the vehicle was finished, the measurements were divided over 60 calibration-days spread over five years. Kalibra has been overall responsible for both parts of the project. The subcontractor for the development of the measurement system was TNO Automotive in Delft, the Netherlands. The subcontractor for the building of the custom-built trailer was Nooteboom Trailers BV in Wychen, the Netherlands. Furthermore, there were a number of other subcontractors for specific parts of the project, e.g. the axles and the tyres.

In order to minimise costs for both Kalibra and DWW and to allocate the costs fairly, the contract negotiations were conducted in an open atmosphere. Both parties were fully open about which costs were expected to be carried by Kalibra and which would be fair to be accepted by the DWW. This way the DWW only paid for the costs that were directly related to the WIM-specific adaptation, while Kalibra only paid for the 'standard' truck and the trailer, custom-built for the static calibration of weigh bridges. The costs for the construction of the vehicle amounted to approximately Euro 600.000,--, to be paid by Kalibra. The costs for the WIM-specific parts, measurement systems and adjustments, approximately Euro 375.000,--, were paid by the DWW. Despite the risks involved in building a prototype the contract between DWW and Kalibra was a fixed price contract.

### Measurement principle
The objective is to measure the force of one axle as directed between the tyre surface and the pavement ($F_p$). This is done by load sensors in combination with accelerometers. The load sensors (strain gauges) are mounted on the measurement axle between the spring centre and the wheel nave. These sensors measure the force of the trailer on the axle ($F_a$). This has to be compensated for the movement of the axles in order to get the axle load ($F_p$). This can be done by measuring the measured vertical acceleration (a) of the wheels and multiply it by the mass of the wheels ($m_w$). $F_p$ is calculated using the following equation (1). A more detailed description of the measurement principle is given in [Hoogvelt, 2004].

$$F_p = F_a - m_w * a \qquad (1)$$

### Specific adaptations
The vehicle consists of a combination of a three-axle tractor with a five-axle trailer with a total length of 16.5 m. The maximum load is 44 tonnes, which results in a total maximum vehicle weight of 78 tonnes. Specific adaptations were made both to the tractor and the trailer.

The standard tractor has been replaced by a 6 x 4 DAF XF with *530 hp*. The extra hp were necessary to be able to accelerate the total vehicle weight quickly enough to the required maximum speed of 100 km/h. Quickly means within 3.5 km, the distance between the WIM-Hand test site and the anticipated turning point. The measurement equipment and two of the liftable axles of the trailer can be controlled from the cabin. These two axles can be lifted when driving and can be controlled by a set of special buttons in the dashboard in the cabin of the tractor. The control of the measurement system is done in the cabin on a laptop

PC with a wireless Ethernet connection to the measurement computer in the trailer. The measurement data can be saved on a CD or stored in the measurement computer. The cabin, a so-called space cab, has air conditioning and a safe for the storage of theft sensitive (computer) equipment.

Because of the required high total weight, a semi-trailer with five axles was selected. In order to avoid great friction in short curves, the axles two to five are steerable. The first axle is the measurement axle and is not steerable, see figure 2. Four of the five axles may be lifted (axles number 1, 2, 4, and 5). This way several axle loads can be realised on the measurement axle without changing the mass of the trailer. When the vehicle is not performing WIM-related measurements the measurement axle will be lifted to avoid unnecessary wear and tear of the sensors.



Figure 2. Numbering of the axles.

Axles 2 and 4 can be lifted during driving, these axles will be lifted just before arriving at the WIM-system. This way the maximum load is not applied to the other axles any longer than necessary. This was necessary because the safety of the axles and the tires is guaranteed only for short distances at maximum speed and maximum axle loads. The tires are filled with nitrogen for heat conduction and to keep them up to pressure. The lifting of these two axles during driving is not possible in a standard hydraulic system, which is why an axle lift system has been designed that is capable of lifting the axles even with the highest axle loads. This system has a larger hydraulic pump than normal, with electronically controlled hydraulic valves.

To guarantee the maximum braking retardation, even when some of the axles are lifted, the ABS-system has been adapted. For instance, the ABS-sensors have been moved to axles 1 and 3 from the normal axles 2 and 4 because these axles will be lifted. All these adaptations to the trailer meant that a new type-approval was necessary.

**Calibration**
The calibration of the sensors of the instrumented vehicle was performed by TNO, a detailed description of the calibration is given in [Hoogvelt, 2004].

*Tracability*
The tracability is one of the key issues for certification of WIM-systems. The calibration of the instrumented vehicle is an important link in the tracability chain of WIM-systems.

The tracability chain consist of the following steps:
- a certified mass (certified by the NMI);
- a certified pressure gauge (certified by the NMI);
- the certified shaker used for the calibration of the vehicle (certified by the NMI);
- the instrumented vehicle (certification by the NMI in progress);
- the WIM-systems for automatic enforcement (certification by NMI in preparation).

The use of a certified instrumented vehicle for calibration will be an important part of the criteria for certification of a WIM-system. In the Netherlands the NMI performs all test for certification of measurement instruments for enforcement agencies. Therefore, the NMI is the most logical institute to perform tests for certification of WIM-systems. How this will be organised in Europe is part of the REMOVE-proposal. REMOVE stands for Requirements for EnforceMent of Overloaded Vehicles in Europe. The objective of the project is to provide a framework within both new and existing Weigh-in-Motion systems can be operated at

strategic and tactical level across the European Community, in order to reduce the danger and damage caused by overloaded vehicles.

*The calibration*
The calibration was performed after mounting the measurement axle on the trailer. For the calibration the axles 2 to 5 were placed on a fixed platform. The wheels of the first (measurement) axle were each placed on a hydraulic shaker. The calibration of the strain gauges is done by applying a range of known static forces on the wheels of the axle. The relation between the measured load and the applied force proved to be linear. The calibration of the accelerometers was done by applying a series of known dynamic forces to the wheels using the same shaker set-up. The wheels were energised with an amplitude of 1.5 mm at three nominal loads with frequencies varying from 1.0 to 13.5 Hz. This way two important eigenfrequencies of the trailer were exercised. The calibration must be repeated every three months over the first year. The results of the calibration are also shown in [Hoogvelt, 2004]. Based on the results of these calibrations the interval between calibrations may be decreased to 6 months and later possibly even to 1 year.



Figure 3. Calibration of the vehicle.

The quality of the measurement data is relatede to the uncertainty to its the static behaviour and its dynamic behaviour of the used equipment. The uncertainty of a measurement by calibration of the standard is given by:

$$U^2_{standard} = U^2_{static, standard} + U^2_{dynamic, standard} \qquad (2)$$

$U_{standard}$       : over-all uncertainty of the measumentvalue of the standard

$U_{static,standard}$       : uncertainty of the sum of uncertainties, dealing with static influences

$U_{dynamic,standard}$       : uncertainty of the sum of uncertainties, dealing with dynamic influences

The uncertainty of the used standards has been calculated by doing a lot of tests and simulation of the system. The uncertainy of the standard system has been determined by calculating the uncertainty of each component of the calibration system of the standard system at the truck according the procedure given at theEA-4/02 [EA, 1999]. From this we calculate the values of the uncertainty of the static influences. The uncertainty of the dynamic influences has been done by calculating the standard deviation for a lot of tests at the same circumstances of the standard system at the laboratory.

## USE OF THE VEHICLE

### Measurement principle

To be able to compare the measured signal from the WIM-system with the data measured by the vehicle, both systems must be synchronised. This is done using the exact time of the GPS-signal as a time reference for both systems. At first a DCF-77 receiver was considered. However, the time signal is not accurate enough (±25 ms) to be used for synchronisation. With the GPS-receiver the maximum difference in the time synchronisation is less than 10 µs. At the maximum speed of 100 km/h with a length of the tire/road contact surface of 30 cm, the contact time of the wheel on the sensor (width of 5 cm) is 12.6 ms. The sample frequency of the vehicle is 8 kHz and of the WIM-test system 8192 Hz (0.12 ms). This amounts to approximately 100 samples per axle load measurement.

The output from a WIM-sensor is similar to the signal (red line) shown in figure 4. The axle load is determined by calculating the area (A) under the signal between the start time ($T_s$) and the end time ($T_e$). The start time is the moment the signal is higher than a certain trigger value ($V_t$), the end time is when the signal drops under that value again. The axle load measured by the WIM-sensor ($F_s$) is calculated by way of the following formula:

$$F_s = (V / L_s) * A * C \tag{3}$$

V is the velocity of the vehicle, $L_s$ is the sensor width and C is the calibration factor. In the currently used standard post-processing the start time ($T_s$) is considered to be the measurement time of the axle load measured by the WIM-sensor [Helg, 2000].
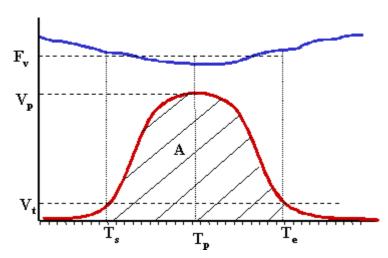
Figure 4. Example of signals measured by WIM-sensor (red) and vehicle (blue).* remark, both lines in figure 4 are examples to explain the measurement principle and not actual measurement signals.

The output from the measurement axle is similar to that of the blue line in figure 4. The axle load is calculated by taking the weighed ($W_i$) average of the measured samples from start to end time:

$$F_v = \sum_{i=Ts}^{Te} W_i * F_i / (T_e - T_s) \tag{4}$$

The weighing factor $W_i$ may be used to adjust for the variation of the load exerted on the WIM-sensor when the wheel rolls over the sensor. Depending on the magnitude of the this variation the weighing factor can be 1 (no variation) or for example 'Bell-shaped' similar to the signal measured by the WIM-sensor.

### Standard operational procedure

The load on the trailer is 44 tonnes, consisting of 44 mass pieces of 1000 kg each and a fork-lift truck for the on and off loading of the mass pieces. This way every axle load between 3 tonnes and 15 tonnes may be realised on the measurement axle. All mass pieces are certified and traceable to international standards. The lifting of the measurement axle is also used to compensate eventual off-set of the force sensors. This 'zero-

setting' of the axle is done at the beginning of each measurement day. The lifting of one or more axles causes a change in the 'driving height' of the trailer. This change is detected and displayed, so the driver can adjust it electronically. The vehicle has a set of special permits to be allowed to drive with 70 tonnes at 100 km/h with axle loads of up to 15 tonnes. Nevertheless, the vehicle is detected as overweight by the WIM-NL systems, the systems used by the enforcement agencies, see figure 5.

The type approval test of the WIM-Hand test site will consist of a large number of different runs by the instrumented vehicle.

The runs differ in the following aspects:
- different axle loads on the measurement axle, i.e. 5, 10 and 15 tonnes;
- different speeds, i.e. 40, 60, 80, 100 km/h;
- different axles configurations, that is axles 2 and 4 lifted, or axles 4 and 5 lifted;
- different ways of driving over the WIM-system, that is accelerating, braking, and zigzagging;
- and during different weather conditions, e.g. different temperatures, rainy spells, over dry or wet surfaces, etc.



Figure 5. The instrumented vehicle in action.

Which tests are deemed necessary for the type approval test is determined in cooperation with the NMI. The time interval between two calibrations will be determined based on the results of the type approval test. An example of the measurement results from the instrumented vehicle is shown in figure 6. The difference in the aplitude of the axle-hop frequency between the right and left wheel was caused by a difference in the pressure in the tyres.The blue lines only indicate the relative position of the sensors within in the WIM-Hand test-site. The absolute position of the sensors of the test site cannot be given since the test-site is not operational yet.

## Additional applications

Although the instrumented vehicle was built for the purpose of calibrating the WIM-Hand test-system, the vehicle can be used for a number of other applications as well.

Possible other applications are:
- Calibration of static weigh bridges or weighing scales;
- Calibration of other WIM-systems. For this calibration it is necessary that the measurements of the vehicle can be synchronised in time with those of the WIM-system;
- Effects of road surface irregularities on the dynamic loads. Possible areas of interest are the dynamic loading of bridges, spatial repeatability, or other issues in vehicle road interaction.
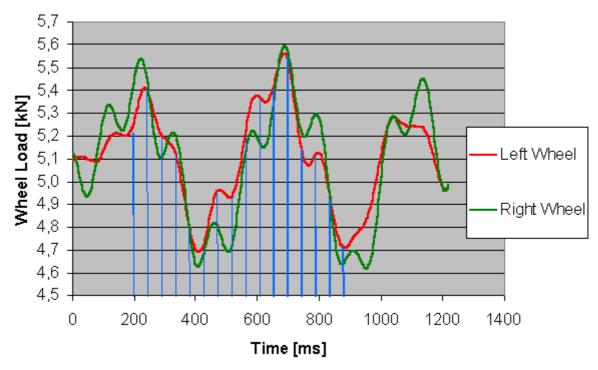


Figure 6. Measurement results.

## CONCLUSIONS

- An instrumented vehicle for the dynamic calibration of Multiple Sensor WIM-systems has been build by Kalibra International for the Road and Hydraulic Engineering Institute of the Dutch Ministry of Transport, Public Works and Water Management.
- The key specifications for the vehicle are: static axle loads between 5 and 15 ton; vehicle speeds between 50 an 100 km/h; a maximum inaccuracy of the measurements of 5%.
- The synchronisation between the instrumented vehicle and the WIM-system is done by using the same time signal from a GPS receiver.
- Unfortunately the WIM-Hand test-site is not operational yet so the validation of the measurements from the instrumented vehicle has not been performed.

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