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Weigh-in-motion of
Axles and
Vehicles for
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Weigh-in-motion of Road Vehicles for Europe (WAVE)

Report of Work Package 3.2

Calibration of WIM systems

TECHNICAL RESEARCH CENTRE
OF FINLAND
Communities and Infrastructure

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THE PROJECT

'WAVE' (**W**eigh-in-motion of **A**xles and **V**ehicles for **E**urope) is a research and development project of the fourth Framework Programme (Transport). Concerned with the weighing in motion of road vehicles, the project ended in June 1999 after two and a half years of steady work. Thanks to an integrated programme with a fruitful collaboration between the partners, and complementary contributions from the participating organisations, significant scientific and technical progress was made and very many results were achieved.

1. Origin of the project

During the COST 323 action (WIM-LOAD, 1993-98), part of the activities of COST Transport, it emerged that further research on WIM was necessary to address the latest requirements of road managers and decision makers. In 1994, the 4^{th} Framework Programme of the European Commission was presented, with a specific "Road Transport" programme. Part of the latter was entitled "Road infrastructure" and a task of this was "Monitoring of factors affecting pavements and structures to support existing and future harmonisation legislation in respect of axle and vehicle weights" (task 7-4/27).

To address this task, a proposal for a large research project, 'WAVE' (**W**eigh-in-motion of **A**xles and **V**ehicles for **E**urope) was submitted to the Commission by a consortium of 11 partners from 10 countries, following the first call in March 1995. A majority of the partners were already participants in the COST 323 action. After a positive review by the experts and a negotiation phase in Autumn 1995, the project began in September 1996, after a 6 month delay for administrative reasons.

2. Objectives

The objective of the 'WAVE' project was to effect a significant step forward for those responsible for road networks, through the following actions :

1.1. Improve the capacity of conventional WIM systems to accurately estimate static loads from measurements of dynamic impact forces applied by axles, through use of arrays of sensors whose combined results can allow for the dynamic interaction between vehicle and pavement.

1.2. Develop and improve the functioning and accuracy of bridge-based WIM systems through more sophisticated vehicle/bridge interaction modelling and data processing.

2. Develop common data structures, formats and quality assurance procedures to facilitate the exchange and comparison of WIM data throughout Europe, to increase confidence in such data and to provide reliable management information to decision makers.

3.1. Perform tests of WIM systems to assess their durability and performance in various climatic conditions, particularly in cold regions where pavements deform and are weaker during the thaw and sensors are susceptible to studded tyres and de-icing salt.

3.2. Develop standardised calibration methods and procedures by improving existing methods and extending their applicability to all European climates and types of WIM system.

4. Develop and implement a new WIM technology, based on an innovative fibre optic sensor which has considerable potential in terms of quality and the extent of information provided and its insensitivity to harsh climatic conditions.

This project constituted a strategic policy initiative to confirm the Europe's leadership in WIM. It led to the development of new technologies such as advanced multiple sensor and bridge WIM systems, a quality assurance procedure to be implemented in a pan-European database, data about the behaviour of WIM systems in harsh environments, an improvement in calibration procedures and the development of a new European optic-fibre WIM technology. That will help road and transport decision makers.

3. Project organisation and means

The consortium involved 6 Contractors and 5 Associate Contractors:

Coordinator: Laboratoire Central des Ponts et Chaussées - LCPC - France

Contractors

Cambridge University Engineering Department - CUED - United Kingdom
Trinity College Dublin - TCD - Ireland
Road and Hydraulic Engineering Division - DWW - The Netherlands
Alcatel Contracting - ALCO (9/96-5/98) / Alcatel CIT Saintes (6/98-6/99) - France
Swedish National Road Administration - SNRA - Sweden

Associated Contractors

Belgian Road Research Centre - BRRC - Belgium
Technische Universitaet Muenchen - TUM - Germany
Technical Research Centre of Finland - VTT - Finland
Swiss Federal Institute of Technology - ETH - Switzerland
National Building and Civil Engineering Institute - ZAG - Slovenia
All together, more than 15 senior scientists and engineers, 25 Ph.D. students, post-doctoral or young engineers or researchers, and many technicians were involved in WAVE. Some subcontractors were SME (Small or Medium Enterprises), manufacturers and/or vendors of WIM systems or services; they were therefore self-motivated and interested in the output and deliverables of the project.

The project was planned for 24 months, from September 1996. A 9 month extension was subsequently accepted by DGVII, which lead to a project completion date of June 1999.

The complete project was organised in 4 main research areas, each of which was divided into two or three parts to give a total of nine work packages (WPs). The WPs were sub-divided into tasks. Each task consisted of work with a specific deliverable or output to be used in another task. Each specific WP covered one of the main objectives of the project and a basic need in Europe. The four main research areas were consistent areas, but had relationships between them. Each WP worked towards providing more efficient and accurate WIM systems and more reliable traffic load data.

The detailed organisation of the WPs is described below:

WP1. Accurate estimation of static weights using WIM systems

- WP1.1. Multiple Sensor WIM (MS-WIM) - *leader: CUED / co-leader: LROP/LCPC*
  - a. New and improved theories
  - b. Validation using experimental data
  - c. Tests of MS-WIM systems
  - d. Specifications and legal issues
- WP 1.2. Bridge WIM systems (B-WIM) - *leader: TCD*
  - a. Increased Accuracy for Typical Bridges
  - b. Extension of B-WIM to Orthotropic Decks
  - c. Extension of B-WIM to Other Bridges
  - d. Dynamic Analysis for Typical Bridges
  - e. Calibration

WP2. Quality, management and exchange of WIM data - *leader: DWW*

- WP2.1. WIM data quality assurance
  - a. Analysis of existing quality systems
  - b. Site quality
  - c. System quality
  - d. Calibration procedures
  - e. Data quality
- WP2.2. WIM data format and database structures
  - a. Submitted data format
  - b. Harmonisation procedure
  - c. Description of two database levels
  - d. Database management and maintenance

WP3. Consistency of Accuracy and Durability

- WP3.1. Durability of WIM systems in cold climates - *leader: SNRA*
  - 0. Preparatory work in advance of the project start
  - a. Reporting previous experience on the subject matter
  - b. Inviting WIM manufacturers to the test
  - c. Final decision on test site localisation
  - d. Site preparation
  - e. WIM installation
  - f. First summer test
  - g. Winter test
  - h. Second summer test
  - i. Random traffic test
  - j. Final report

WP3.2. Calibration of WIM systems - *leader: VTT*
  a. State of the art report
  b. Test of calibration devices and procedures
  c. Specification of the calibration procedures

WP4. Optical fibre WIM systems, technology for the future - *leader: LCPC*

WP4.1. Sensor Design
  a. Feasibility
  b. Characterisation and testing
  c. Calibration
  d. Mathematical model (1)

WP4.2. Optoelectronic Head
  a. Design
  b. Multiple sensor head
  c. Long-term performance
  d. Prototype improvements

WP4.3. Data Acquisition and Processing Unit
  a. Data acquisition and treatment
  b. Mathematical model (2)
  c. Validation and Report

A total budget of 1.5 million Euros was allocated to the WAVE project, of which 0.75 million Euros was provided by the European Commission. The total time spent on the project was nearly 30,000 man-hours, i.e. 20 man-years. The personnel cost represents 69% of the total budget. A mid-term seminar was organised in September 1997 in Delft, The Netherlands (WAVE, 1997) and a Final Symposium in Paris (May 1999), in order to widely disseminate the results of the project. In addition, much of the results were presented at the Second European Conference on WIM organised through the COST 323 action. A Web site was initially built by LCPC and is now merged with the European WIM web site built by the COST 323 action and hosted by ZAG (http://www.zag.si/wim/). A CD-ROM was prepared (edited by the BRRC) to present all the reports and output of the project.

Several large testing facilities or bridge and road test sites were used in the project. Two road sections were instrumented with multiple-sensor arrays, in the UK and France, for testing MS-WIM systems. For the calibration of these arrays, instrumented lorries and pre-weighed lorries were used. Several bridges of different type were instrumented in France, Germany, Sweden, Slovenia and Ireland to develop and test B-WIM systems. For WP3.1 in Sweden, a road section of 0.5 km was instrumented with five WIM systems, and a static weighing area with a large weigh-bridge was used.

4. Project output

New theories, models, algorithms, and procedures have been generated, prototypes built, and field tests performed. New prospects have been opened up for weighing using multiple sensors and instrumented bridges, an innovative technology has been developed using optical fibres and optronics, and there have been significant advances in the calibration of the systems and in the quality and management of weigh-in-motion data. Experiments on roads fitted with sensors and on instrumented bridges have yielded highly valuable quantitative information on the durability, performance, and precision of many types of weigh-in-motion system.

As happens in most active and innovative research projects, many questions have been answered and others asked, opening up new prospects. The scope of weigh-in-motion has been expanded to encompass new needs in the checking of vehicle weights, thanks to a substantial improvement of the levels of precision, and in the design and management of road infrastructure, thanks to new approaches to the instrumentation of roads and bridges.

In addition to performing the research and attaining the project's objectives, the consortium has attached special importance to dissemination of the knowledge and results acquired, both within the scientific community and to the users and industrial builders of the systems. The fallout from such a project is almost as much a matter of "making known" as of "know-how".

Overall results of the project are presented in the General Project Report, published by the LCPC. Detailed results of each WP are presented in each WP's report, which are published by the WP leader's organisations.

Report on the WP 3.2

This report was drafted and is edited by Matti Huhtala.

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1. INTRODUCTION

Even the WIM-systems themselves were perfect, calibration is needed because of site dynamics and local traffic conditions.

Each new WIM installation will have different characteristics, for example pavement construction, which will cause vehicles to behave in different ways. In order to minimise the effects of these factors on the accuracy of the WIM measurements each new site requires calibration.

In addition to local differences in site dynamics the types of traffic will affect the measurements. In particular the normal types of suspension and loading will, combined with the site dynamics, require unique calibration figures for the local conditions.

A number of factors influence the accuracy of static load estimation by weigh-in-motion and may induce some load transfer from axle to axle, or some bias to the axle loads:

- the body bounce, pitching and axle hop motions,
- the aerodynamic forces applied to the vehicle,
- the driving torque,
- the local pavement deflection and evenness,
- the sensor response and its shape with respect to time or its extension in the traffic direction.

Among these factors, some are related to the vehicle and its driving conditions, others to the road, and the last ones to the WIM sensor and system. Moreover, the vehicle motions are mainly induced by the road profile. For a given WIM system, installed on a road, it is expected that some of these effects are repeatable, if related to the pavement and sensor. In such a case, an appropriate calibration could improve the static weight estimation.

Terms like accuracy and precision are defined at ISO-documents but are still used in different ways. Accuracy can be defined as the closeness of a measurement to the true value being measured and precision as the closeness with which the measurements agree to each other. That can be described graphically like in Figure 1 (modified from Papagiannakis 1995). “Not precise” can be expressed also with the word “scattered”.

Bias can be described graphically as in Figure 2 and is used in that way at least in electrical engineering and in electrical measurements. The ISO definition is somewhat more general.

This report handles the calibration issues in European Commission IV Framework RTD project WAVE (Jacob 1997, Jacob & al 1999). This Work Package 3.2 report is closely associated with Work Package 3.1 report (Hallstrom & al 1999) which handles the test at Lulea in Sweden and COST 323 tests at Metz in France and not all details are described in this report. Especially the accuracy aspects and results are not repeated in this report.

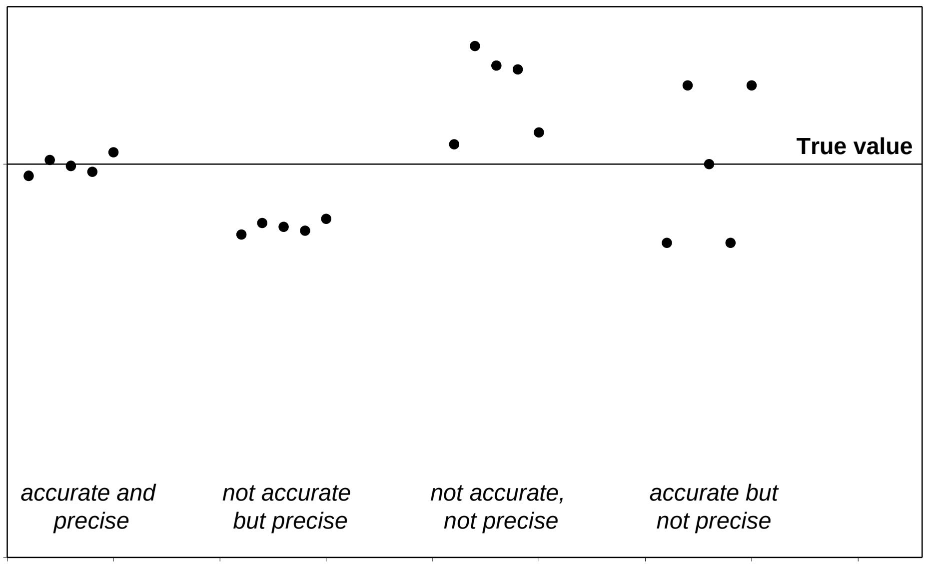


Figure 1. Definition of Accuracy and Precision.

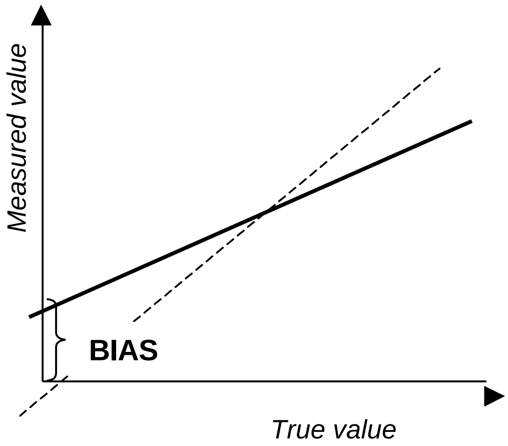


Figure 2. Definition of bias.

2. FACTORS AFFECTING ON THE ACCURACY OF WIM SYSTEMS

2.1 Dynamic loading

As a heavy vehicle drives on the road the axle load is not a steady, let say nominal 100 kN, but it may vary up to ±15 (or more) percent even on a good road. The basic reason is the unevenness of the road. The amount of dynamic loading depends on the quality of the suspension and on the speed of the vehicle.

The main movements of a vehicle are (Figure 3):

- body bounce, which means pitching and bouncing of the vehicle body, natural frequency usually 1.2 to 3 Hz, lower limit corresponding good up to date construction of suspension and upper limit poor old stylish suspension
- axle hop, natural frequency usually around 10 Hz.

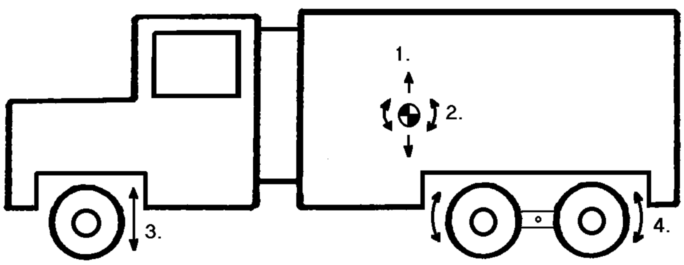


Figure 3 Dynamic movements of vehicle, body bounce (1),body pitch (2) and axle hop (3) and tandem pitch (4)

There are other movements, too. Because WIM systems are installed on straight road sections there is, however, very little rolling and other movements than body bounce and axle hop. Harsh weather conditions, for instance wind or ice on pavement may excite dynamic movements, too.

If a vehicle passes the same road at the same speed the dynamic loadings will be the same; there is then a perfect spatial repeatability (an example in Figure 4). If there are several vehicles the extent of spatial repeatability varies. It depends on the single unevenness of the road; after a single uneveness there may be a perfect spatial repeatability but on an even road section none can be detected. The dynamic loadings on a road caused by several vehicles with different speeds are not fully known.

Spatial repeatability has been handled in several references (Huhtala & al 1992, Cole & Cebon 1992, Gyenes & Mitchell 1992, Huhtala & al 1993, Huhtala & al 1994a, Huhtala & al 1994b, Huhtala & Halonen 1995, Huhtala & Jacob 1995, O'Connor & al, Dolcemascolo & Jacob 1998).

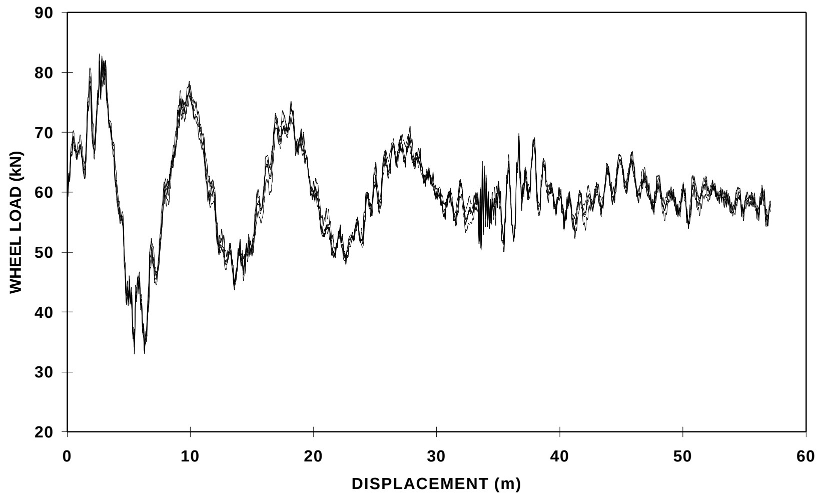


Figure 4 Repeatability of dynamic loadings, five vehicle passes

The information which is needed from WIM is generally not the dynamic loading but the static loading or the axle loads and gross-weights of the vehicles.

In order to minimise the effects of dynamic loadings on the accuracy of WIM system the road before the WIM system must be as even as possible. It is important to note that even the road is very smooth and the suspensions are good there is always some dynamic loading, in practice the axle load varies at least ± 10 %.

2.2 Different types of sensors and WIM-systems

2.2.1 Bending plate

The WIM system may be a steel or aluminium plate (bending plate or supported by stress sensors), with strain gauges or load cells. The width of the plate is such that the whole wheel is on the plate. Thus the weight of the wheel can be directly measured. Because of the principle of a plate, such a WIM system can be calibrated in principle with calibration masses. The response of such plates is usually not depending on the speed of the vehicle nor the ambient temperature. Bending plate WIM-systems are described more in detail for instance in a WAVE WP 3.1 report (Hallstrom & al 1999).

2.2.2 Strip sensors

The WIM strip sensors are piezoceramic, piezoquartz, capacitive, fibre optics, etc. The main characteristic is that the width of the strip sensor is only a small part of the imprint of the passing tyre and thus the stress or corresponding signal from the sensor must be integrated. If the integration is not perfectly done, the result may be sensitive to the speed of the vehicle. These sensors are low cost sensor and the installation work, time cost and also all damage induced to pavement are reduced because these sensors are narrow.

The contact area between the tyre and pavement (tyre imprint) varies due to the tyre type, wheel load and tyre inflation pressure.

The sensitivity of the sensor may be inhomogenous or some parts of the sensors are more sensitive than others. This type of sensors are often sensitive to ambient temperature; thus a temperature compensation may be necessary.

2.2.3 Multiple sensor WIM

Multiple sensor (MS) WIM system means that there are usually several strip sensors, each of which measures the wheel or axle load of a passing vehicle. In principle multiple sensor WIM system could be designed with several bending plates, but the cost would become quickly dissuasive. If the sensors are suitably spaced the mean value would omit the effect of dynamic loadings and could provide the static weight. In reality the situation is much more complex, there are always several spatial frequencies (at least two ranges of vehicle eigenfrequencies, modulated by the vehicle speed) and the sensors must be very homogenous. Therefore more advanced and sophisticated algorithms are being developed to increase the efficiency of MS-WIM, Siffert et al. (1997).

Multiple sensor WIM systems are promising but are still in a development prototype phase. Field experience is available only on a few sites and limited periods, Barbour and Newton (1995), Jacob and Dolcemascolo (1997a), Blab et al. (1997). Multiple WIM-sensors have been further developed in WAVE project (WAVE- project, Report of Work Package 1.1).

In certain cases there are only two sensors. In that case problems are smaller but also the increase in accuracy is smaller.

2.2.4 Portable WIM-systems

Portable WIM-systems are installed on the surface of the road for temporary use. The advantage is that they can be used in one place for certain time and then move to another place or there use may be very effective and costs relatively low.

The weighing sensor is usually a capacitive mat or capasitive strip. There are two or three plates of a capacitance which are separated by a synthetic dielectric material with well known elastic property. The capacitance of the mat depends on the distance between the plates and its change is measured by a frequency variation. Some portable WIM-systems are described in a COST 323 report (Blab et al 1998).

2.2.5 Bridge WIM-systems

In the bridge WIM-system the whole bridge acts as a measuring system. Strains and/or elongements are measured in carefully selected points at the bridge. The calibration differs from other WIM-systems.

Bridge WIM-systems have been developed further within WAVE project (WAVE-project, Report of Work Package 1.2).

2.3 Calibration methods

2.3.1 Calibration masses

They can be used only on bending plates and large scales. They can distinguish possible differences along the plate. These masses do not take into account the effect of dynamic loadings, neither the specific tyre impact, and can be used only as the first step of calibration.

2.3.2 Calibrated forces or shocks

Vehicle wheel load may be simulated with calibrated concentrated load or shocks, such as with a Falling Weight Deflectometer (FWD). A prototype device was also developed in France to test and calibrate the strip sensors in laboratory (®Piezodyn) by Gatti and Viano (1995). It applies a vertical sine wave pressure on the sensor and records the average of the maxima over a few periods. This device was tested on a road in the frame of the OECD/DIVINE project (Element 5), Huhtala and Jacob (1995).

2.3.3 Pre-weighed vehicles

Preweighed or test vehicles are vehicles which are provided by the user or the supplier of the WIM system. The axle loads are measured statically and they pass several times the WIM system. Their pay-load and speed may be varied. The number of pre-weighed vehicles is usually limited to 2 or 3, of different types (silhouettes), representative of the vehicles to be weighed.

2.3.4 Vehicles from the traffic flow

Vehicles from traffic flow are stopped and their axle loads are weighed, either statically or sometime on a low-speed WIM system with an approved accuracy level much higher than the expected one of the WIM system to be calibrated. Thus there are several types of vehicles with several kind of tyres, axles, suspensions, etc. Each of them makes only one pass.

2.3.5 Automatic self-calibration procedures

These procedures, initially developed in France by Stanczyk (1984), use the knowledge that some types of vehicles have rather constant loads on one or two of their axles; such vehicles are called 'characteristic vehicles'. It concerns often the front wheels or axles but even passenger cars may be used as characteristic vehicles. If there are enough characteristic vehicles in the traffic flow, it is possible to develop an automatic self-calibration procedure by software which can correct the drift or variations in the sensitivity of sensors due to temperature or other effects. The principle is to fit a moving average of the characteristic vehicle axle loads on the target values known by experience, Stanczyk (1991).

2.3.6 Instrumented vehicles

Instrumented vehicle measures continuously the real dynamic axle load. The dynamic load is matched to the place of the WIM sensor. If the system works well with perfect match and reliable dynamic load measurement this would be ideal for the calibration of WIM systems. There is only little experience by the present time, but it was used to calibrate a MS-WIM array in France during the OECD/DIVINE project, Huhtala and Jacob (1995). There are problems like what is the accuracy of the measurements, how the unevenness of the road may affect dynamic loading, how accurate is the matching of dynamic loading measured in the vehicle and corresponding WIM-reading. Because there is no exact method of calibrating the instrumented vehicle the real accuracy of the measurements is not exactly known. However, there is no special doubt about the accuracy of the present calibration systems. (Leblanc et al. 1992).

Instrumented vehicle as a calibration tool is further handled in this report in chapter 4.

2.3.7 Bridge WIM calibration

Trucks of known weight are used to calibrate bridge WIM systems. Test plan 2.1 from the draft European specification of WIM (COST 323, 1997) is highly recommended. It applies 2 trucks, one 2- or 3-axle rigid and one 4 to 5 axle trailer or semi-trailer. Each of these should be driven 10 times in each lane with 3 different speeds. Loading close to the expected mean gross weight should be used. Several additional runs with unloaded or half-loaded vehicles can be useful to verify measuring parameters that were input to the system. Calibration results should not exhibit any nonlinearity due to the loading or speed of the vehicle. If this occurs, influence lines, speed acquisition procedure and other input parameters (dimensions of the structure, locations of the transducers etc.) have to be checked.

If test plan 2.1 can not be provided, at least test plan 1.1 from the same draft specifications (10 runs of one truck with 2 or 3 different speeds) should be used in each lane. A shorter, 2 or 3-axle rigid truck is recommended as it can often indicate possible dynamic problems. Compared to the longer non-rigid vehicles, they are also more sensitive to the uneven pavement and bumps before the bridge, thus providing a more realistic indication of the expected accuracy of WIM results.

As long as there is no major bump on or just before the bridge, the roughness of the pavement has a lesser effect on bridge WIM than on pavement WIM systems. If a bump is present, some vehicles, especially the shorter rigid trucks, can jump on or even over very short bridges or culverts. The International roughness index (IRI) is of little help for bridge WIM since it does not account for such local situations.

If influence lines are applied in the bridge WIM algorithm, their appropriate selection is a most critical factor for the accuracy of the weighing results. The influence line describes the behaviour of the structure under moving load and is, for the bridge WIM application, defined as the bending moment at the point of measurement due to a unit axle load moving along the bridge. The true influence line of a single span structure (bridge, underpass or culvert) generally lies between those for ideal simply supported and completely fixed beams or deck slab (Figure 5, top). A similar situation occurs with bridges over more than one span (Figure 5, bottom). Furthermore, due to the thickness of the superstructure (beams and deck) and/or when there are no expansion joints between the bridge and the pavement, the influence line can be extended beyond the centre-lines of the supports (Figure 5, top, dotted lines).

The greater the difference between the integrals of measured and theoretical strains (areas under the corresponding influence lines), the higher the error of the results. Very often the error of the gross vehicle weight remains within acceptable limits even with poorly matched influence lines, but the axle weights can be severely redistributed. Therefore, a strongly recommended way to reduce these errors is to apply as accurate an influence line as possible, preferably by processing the measured strains at the site. If appropriate computer tools are available, this can be easily done during the calibration procedure.

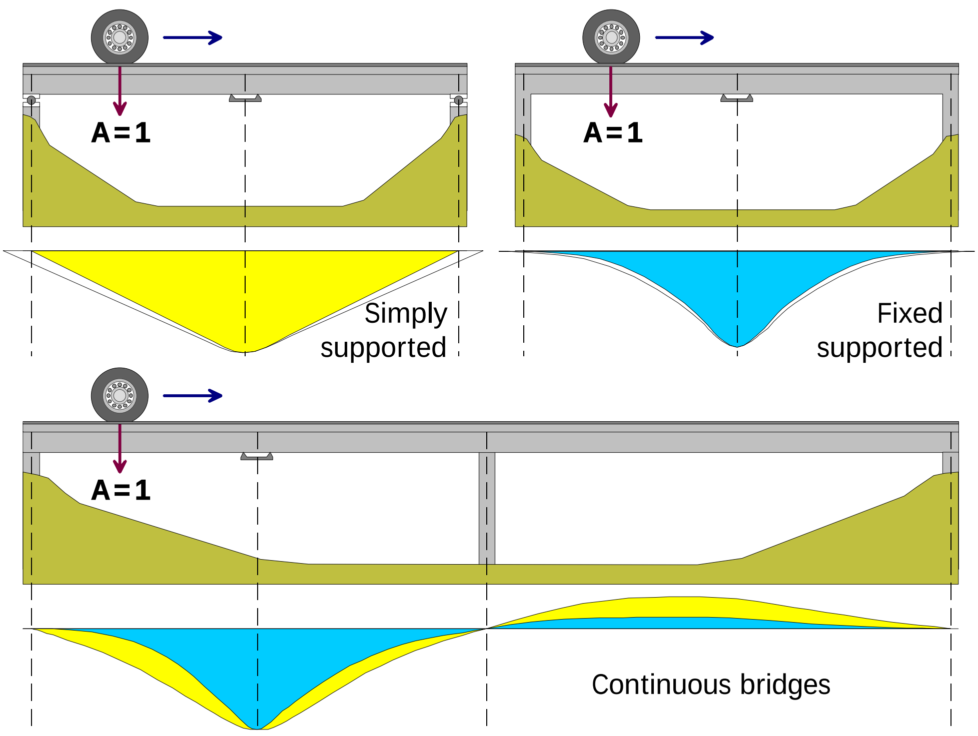


Figure 5 Influence lines for simply and fixed supported (integral) bridge over 1 and 2 spans

Before starting the calibration of a bridge WIM system with pre-weighed trucks, all signals from strain transducers and axle detectors should be checked to determine that they provide reasonable values. If one or more of the transducers give suspicious values it is recommended to inspect their attachments to the structure and the connections between cables before proceeding with the calibration process.

The influence of weather or temperature on bridge WIM calibration should be small. However, to account for the possible effect of a change of the asphalt pavement stiffness on calibration factors, it is recommended to repeat the calibration in extremely different temperature conditions (during two summer and winter days or at least, on a sunny day, before and after sunset). Only in some extreme cases (e.g., if the expansion joints are badly maintained or if an integral, frame-type bridges over freezing water is instrumented) the temperature may have major effects on bridge behaviour and consequently on bridge WIM results.

2.4 Links to metrological calibration

The relationship and links with the official legal metrological requirements for calibration of automatic weighing systems (OIML 1992, OIML 1996) is described in Jacob (1997). These requirements mainly refer to traceable procedures and are used for legal applications such as commercial weighing and enforcement. But they generally may not be fully applied to High-Speed (HS) WIM systems.

2.5 Test plan and data analysis for calibration

While the scope of the OIML recommendation is the legal measurements, the metrological concepts are used, with the specification of maximum permissible errors (mpe); it means that 100% of the measured values must be within the specified interval, centred on the static weight, for a given accuracy class. But this definition may not be applied for WIM on common road in the traffic flow, because the road and traffic conditions are not fully controlled and known, and therefore the measurements are not fully repeatable (no traceability). Then the maximum error does not have any upper bound. For HS-WIM, or in some cases LS-WIM without a strong control of the vehicle travelling conditions, only a statistical approach may be used, Jacob (1997).

Such an approach for accuracy assessment and calibration of WIM systems is developed in the European Specification of WIM, COST323 (1997). This specification contains various calibration procedures and calibration checks by testing. The following cases using pre-weighed lorries and vehicles from the traffic flow are considered, both for calibration and testing:

Full Repeatability Conditions (r1): One vehicle passes several times at the same speed, load and lateral position.

Extended Repeatability Conditions (r2): One vehicle passes several times at different speeds, different loads and with small variations in lateral position (in accordance with typical traffic).

Limited Reproducibility Conditions (R1): A small set of vehicles (typically 2 to 10), representative in weight and silhouette of typical traffic, is used. Each vehicle passes several times, at different combinations of speed and load and with small variations in lateral position.

Full Reproducibility Conditions (R2): A large sample of vehicles (some tens to a few hundred), taken from the traffic flow and representative of it, is used for the calibration.

Usually the following entities are considered:

(a) the single axles,

(b) the axle groups,

(c) the axles belonging to an axle group, taken individually,

(d) the gross weights.

The definition of an axle group is a set of (two or three) consecutive axles spaced less than 2 m (this value is not standardised, and may varies from about 2 to 2.3 m). A group of two axles is called a ‘tandem’, while a group of three axles is called a ‘tridem’.

3. CALIBRATION SYSTEMS USED AT CET

3.1 PAT

PAT uses bending plates, which are large enough to weigh the whole real wheel load as it is for a moment totally on the plate. Thus no integration of signal is needed and in principle only the greatest weight is recorded as the wheel load passes over the bending plate. In reality the measurements system is more complicated.

The PAT bending plate consists of a solid elastic steel metal plate with an integrated network of strain gauges. The bending plate sensor is installed in an independent metal frame and can be exchanged if necessary. The sensor is completely covered with hot vulcanised rubber for durable humidity and corrosion protection.

PAT uses two sensors, one for each wheel path and thus certain comparisons between the results from them can be made. Inconsistency between those two is expressed as violation codes and that data can be removed.

Calibration is divided into

- calibration of speed and axle spacing,
- calibration of vehicle length and
- calibration of vehicle weight

Axle spacing, speed and vehicle length first calculated from distances between loops etc and final tuning is made with a few vehicle passes.

The system is nonlinearly speed dependent. If possible the first test speed is at 10 km/h (difficult on motor roads) and then usually 25, 40 and 56 mph. (speeds in Europe are slightly different because they are in SI units).

No temperature correction was originally needed. The temperatures at Lulea were so low in December 1997 measurements that a new formula for temperature compensation was needed and was developed by PAT.

It was decided that all PAT results since December 1997 would be analysed also with the temperature compensation given by the manufacturer. Temperature compensation is based on results of the December 1997 test and is formulated, as follows:

temperature above +5: no compensation

below +5: factor = 1 + ((5 - temperature)/5)x 0,03

Temperature compensation is needed during the cold period. Thus compensation was made only for the data received from tests of December 1997, January and March 1998.

Temperature of the pavement surface varied between –18 and –24 degrees centigrade during the test of December 1997. Temperature compensation works properly under very cold temperature. Under cold temperatures, above –20 but below +5 degrees centigrade, more efficient compensation is needed as can be seen in Figure 6.

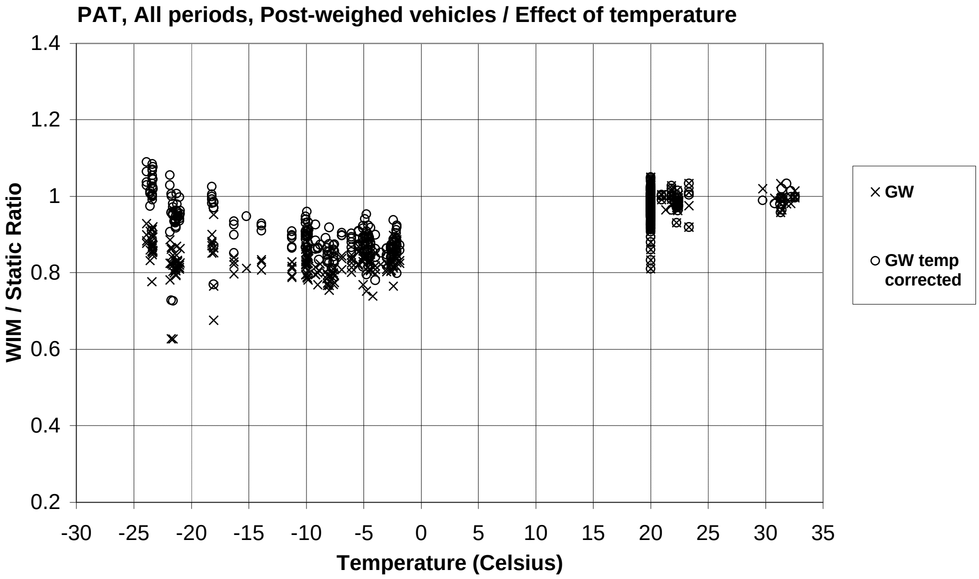


Figure 6 Effect of the temperature compensation.

Minimum requirement is 1 passage for speed calibration, and 3 times 3 for weight calibration. The vehicle is 2 to 5-axle truck which is loaded with solid material like concrete or steel up to the legal limit and should be equipped with air suspensions.

3.2 Datainstrument

Datainstrument has installed two systems at Lulea, one was used and another one was in reserve. They are basically similar and only one was analysed.

Datainstrument uses in their system two sensors fabricated by Philips (Vibracoax), which are installed 3 metres apart. They are piezoelectric ceramic cables inside copper sheets and are installed grooves in the asphalt pavement. The grooves are filled with Sikadur up to the level of the pavement surface.

Datainstrument will start to use sensors from other manufacturer, too.

The sensors are sensitive for temperature, speed and moisture. They do not necessarily affect only directly to the properties of the sensor but also indirectly; bituminous materials are stiffer at colder temperature and moisture may affect on the properties of underlying unbound road materials.

The low end of the scale is calibrated with personal cars. Cars are divided into three categories, small, medium-small and medium. The front axles of personal car of the group medium-small are used for calibration. It is defined as cars with axle spacing between 2.4 and 2.9 meters. The moving average of last 100 vehicles is used for calibration.

The high end of the calibration scale is made by using single axles of heavy vehicles, however not, the front axles. The characteristic value is taken as the 95% of the cumulative distribution calculated from 100 vehicles.

The first axle of the latest 25 to 100 private cars is used to determine the cable signal strength and variation. These reference values is thus updated relatively quickly and is independent of heavier vehicles. When a heavy vehicle passes, axle weight is calculated as a function of the strength of the actual reference signal. The reference signal strength changes continuously during a day as a response to changes in temperature, humidity and asphalt viscosity. If the reference signal level is high, a high signal strength is required to calculate a heavy load. A low reference signal level accordingly requires lower signal strength.

Selected 'heavy' axles is used in a feedback and connected to actual signal strength. This means that the system continuously is building a set of reference values for light and heavy axles belonging together. This way the system adapts to a measuring site and changing levels of signal strength as a response to changes in temperature, humidity, and asphalt stiffness. This requires most of the vehicles to pass a site with all wheels of an axle directly over a detecting cable. A complete build of reference values to adapt to a site can take several days.

At first start-up the set of reference values is filled with values based on averaged earlier measurements.

In Sweden the road shoulder is often used by vehicles, almost as a lane number two. Before every test and calibration a set of cones is installed to lead the traffic correctly into the desired lanes. At the end of a test the cones are removed.

At system start-up in June 1997 the Datainstrument system was set up with reference values based on earlier general experience. At test time experienced reference values for heavy axles was used at start-up, while reference values for light axles determined signal strength. In this test results are within +10 to –10 percent. Variation was high, but this was expected to improve as our system was supposed to adapt to the site.

At the end of the initial test the cones leading the vehicles correctly into the lane was removed. Without the cones the vehicles tended to drive closer to the shoulder, and even at the shoulder. The result was that a lot of vehicles passed the cables with only the left wheels of axles at the measuring cables. It is assumed that heavy vehicles and slow light vehicles tend to use the shoulder more than private cars. The system decided that this was a site with low and varying signal strengths, and the automatic calibration system made a reference set of values based on this driving pattern.

At the following tests the cones again was installed to lead vehicles correctly into the lane. The reference signal strength (based on private cars) rapidly changed as now both wheels of axles was within the cable range. This in turn required high signal strength from heavy axles.

All weights were underestimated due to the erroneous set of reference values made on the base of the atypical driving pattern. The resulted in mean values calculated 20 to 30% too low.

3.3 Kistler/Golden River

Kistler/Golden River uses two strip sensors, which are installed at the distance of 4 metres apart. The system is using four WIM sensor channels, each containing two Lineas sensors (of 1 meter length). The signals of a Lineas pair are added onto one amplifier channel.

Thus every axle is weighed by four sensor pairs:

- Channel 1: First sensor pair, right wheel-track
- Channel 2: First sensor pair, left wheel-track
- Channel 3: Second sensor pair, right wheel-track
- Channel 4: Second sensor pair, left wheel-track

The Kistler LINEAS Quartz sensors used in the Golden River Traffic WIM system are linear in their output (charge output against force applied) and have little temperature sensitivity (less than 1% per 50 ºC, from –50 ºC to +80 ºC).

All Lineas WIM sensors are calibrated during manufacture to ensure that all are within a sensitivity band. Each sensor is also individually tested to ensure the linearity of this sensitivity along it’s length. This linearity allows the Golden River System to use a very simple calibration technique with a single number, or ‘calibration factor’ representing the site’s affect on each sensor.

During calibration the WIM System compares each test vehicle which passes over the site with the known weight and calculates ‘calibration factors’ for each sensor (for each wheel impact). These calibration factors are noted and, at the end of the calibration these factors are simply averaged to give a single calibration factor for each sensor.

At the Lulea test site three test trucks were provided and were run through at different speeds and with different loads.

3.4 Omni Weight Control

The sensor of the OWC system is a steel frame, which is installed on a prefabricated concrete bed. The sensor is horizontal and covered by asphalt mixture of about 70 mm at the shoulder side of the road and about 200 mm in the centreline. The asphalt mix is compacted in a net against the steel box in order to ensure good bond between the asphalt and the sensor.

The whole sensor is inside the road and nothing but the new asphalt can be seen. The advantage is that there will be no problems because of winter maintenance (ploughs etc) or studded tyres. If it is necessary to repave the road because of rutting, it can be done over the sensor; only new calibration is needed.

In the current installation the steel structure is roughly 350 cm x 180 cm x 18 cm and inside it there are ten active strain gauges. Every strain gauge has a passive duplicate glued near it. This reserve gauge is activated automatically if there are problems with the primary gauge.

The strain information is sent to a box by the roadside where the computer linearizes the data with a neural network to kilograms. This weight information is combined with time information and passed to a different neural network that detects vehicles from the stream and classifies them in their proper groups.

Neural network is a name for a very wide variety of different mathematical methods that are used for linearization, classification and control purposes just to name a few areas. OWC uses two different neural networks on two places in the system. The first one linearizes the strain data to simple kilograms. This network could be replaced with a simple mathematical function, but a neural network gives more space for later modifications than a simple function. The second network classifies the passing vehicles into different groups depending on the country's specifications. OWC used neural networks mainly to be able to tailor the system to different conditions without resorting to modifying the underlying software.

The final data is placed into a database from which it can be retrieved either directly by modem or if desired through the internet. From the internet side the scale would look like a normal www-page that the scale automatically updates.

The system must be calibrated (or taught) by loading it with passing vehicles. At least four weights and three speeds are needed. Calibration must be done at different circumstances, especially at different temperatures.

OWC system is a prototype and this model has never been installed in a real road before the Lulea test. Later the Finnish National Road Administration has ordered two WIM-systems, which have been installed on National Road 7 in June 1999.

4. INSTRUMENTED VEHICLE AS A CALIBRATION TOOL

4.1 Instrumented vehicle

The information which is needed from WIM is generally not the dynamic loading but the static loading, or the axle loads and gross-weights of the vehicles.

The road before the WIM system must be as even as possible in order to minimise the effects of dynamic loadings on the accuracy of WIM system. It is important to note that even the road is very smooth and the suspensions are good there is always some dynamic loading, in practice the axle load varies at least ± 10 %.

If a vehicle passes the same road at the same speed the dynamic loadings will be the same; there is then perfect spatial repeatability. If there are several vehicles the extent of spatial repeatability varies. It depends on the single unevenness of the road; after a single unevenness there may be a perfect spatial repeatability but on an even road section none can be detected. The dynamic loadings on a road caused by several vehicles with different speeds are not fully known (Huhtala,1993, 1994).

The instrumented vehicle used at the Lulea and Metz test is owned and instrumented by VTT. It is common three axle rigid lorry in Finland, SISU (Figure 7). The second and third axles establish together a tandem axle. It has traditional steel springs on the front and tandem axle. Both axles of the tandem axle have a mechanical connection and it is possible to lift up the third axle. Due to mechanical connection on tandem axle, axle masses are shared 55 % for the second axle and 45 % for the third axle. Tyre size for each wheel is 10R20 and there are dual tyres on the tandem axle.

Technical information of the instrumented vehicle is presented in Table 1.

Table 1 Technical parameters of VTT's vehicle

PARAMETER	AXLE 1	AXLE 2	AXLE 3
Maximum mass (kg)	6000	8800	7200
Axle spacing (m)	-	4,20	5,40
Spring stiffness (N/mm), estimated	210	1600 550 when 3rd axle lifted up	
Eigenfrequency, Body bounce / Axle hop (Hz), approximately	2,5 / 11	3 / 10	3 / 10

Figure 7 The instrumented vehicle owned by VTT

Some results of eigenfrequencies measured by VTT are presented in Table 1. More detailed spectral analysis was made by LCPC and LROP using the dynamic axle load measurements made at Metz (see point 4.4).

4.2 Instrumentation and calibration

The principle of measuring dynamic wheel loads is implemented by strain gauging the axle housing. Strain gauges are used to measure bending moment of the axle. An inertial force component is measured by accelerometer, see Figure 8.

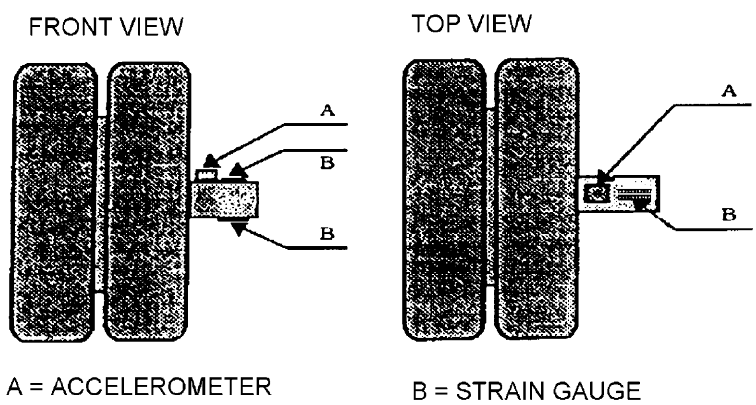


Figure 8 The locations of the sensors on the axle of vehicle

The vertical wheel load measurement method is based on equilibrium of the moments acting on the mass outboard of the measuring point on the axle (place of the strain gauges). On straight road angles of the axle, caused by axle roll, are assumed to be small (there is no curvature on test section). Secondly, distances from wheel load centroid and mass centroid to strain gauges are equal. With these assumptions the vertical wheel load can be resolved in equation:

$$Fw = Fs + Fd + ma$$

where:

Fw Wheel load applied to the pavement

Fs Static wheel load

Fd Dynamic wheel load (deviation from the static wheel load) measured by the strain gauges

m Mass outboard of the strain gauges

a Vertical acceleration of the outboard mass measured by the accelerometer

The data acquisition system consists of amplifiers for the strain gauges and A/D converter mounted in industrial PC. Strain amplifiers carry out signal conditioning for the strain gauge measurement. Accelerometers have a built-in signal conditioning. In addition, digital filtering is used to remove unwanted components. In order to correct phase shift due to filtering, signals are filtered twice (time-reversed signal on second time). Typical sampling rate used is 1000 Hz. Cut-off frequency for the digital filter is 50 Hz.

Dynamic wheel load measurements are matched to the WIM-systems by using an electric eye to detect reflective tapes glued across road lane. Tapes have been fixed every ten meters in order to ensure exact measurements.

A special software is used to link data collected from several sources mentioned above and ensure ready-made data for later analysis.

VTT has made the first dynamic wheel load measurements in 1987. The instrumented vehicle has been used mainly at Virttaa Test Site and on certain WIM research. The system was improved for measurements at WAVE.

The measurement system measures the bending of axle. For many practical reasons the result is the deviation from the static situation. The load is added to the platform of the vehicle stepwise and the wheel load is measured under each wheel. After loading the vehicle is unloaded and although there are steel suspensions no hysteresis has been seen.

Even if the road is relatively even without any sudden unevenesses the effect of the mass outboard of the strain gauges shall be taken into account. The system was calibrated at the Helsinki University of Technology where each wheel was set on a shaker table one axle at the time. The shaker tables were vibrated from 2 to 16 Hz at 2 mm amplitude (peak to peak) and 0.5 - 3.5 Hz at 15 mm amplitude. The wheel loads were measured in the vehicle and in the shaker table system as well as the acceleration by accelerometers. The effective outboard mass of each axle system could be calculated and were used in the measurement system.
Thus the calibration of the dynamic loading system is based on the equation presented earlier:

$$Fw = Fs + Fd + ma$$

Fs (static wheel load) is measured by static axle weighing pad before each measurement series or after the vehicle is loaded (usually empty, half-loaded or full-loaded).

Fd (dynamic wheel load) is the deviation from the static wheel load measured by the strain gauges in the axle. This calibration is made as the vehicle is stepwise loaded and unloaded. It is done basically once in a season.

m (mass outboard of the strain gauges) is defined on the shaker table as a mass (pseudomass) which gives minimum error between the measured values at the shaker table force measurements and dynamic load measurements in the vehicle. The measurements are not very sensitive for the change of the mass (pseudomass).

a (vertical acceleration of the outboard mass) is measured with the accelerometer.

Modified equation used with the instrumented truck:

DWL = Fs*g + Ss*S + m*As*(A-Ao)*At*g

An example:

the dynamic wheel load of the left front wheel (DWL) at time (t) is

DWL = 2850*9,80665 + 7324*S + 360*6,66667*(A-2,4995652)*1,005233*9,80665,

where
A = accelerometer output (Volt) at time (t)
As = accelerometer sensitivity (g/V)
Ao = accelerometer output at 0g (Volt)
At = accelerometer temperature correction
S = strain gauge output (Volt) at time (t)
Ss = strain gauge sensitivity (N/V) and
gravity (g) 9,80665 m/s^2

The basic principle of using instrumented vehicle in calibration of WIM-systems is the following: the instantaneous dynamic wheel load is compared to the WIM-system reading. Exact positioning system is needed in order to synchronise the vehicle measurements to the exact positions of the WIM-sensors. This is usually done having a reflective tape on the pavement each ten metres. An electric eye detects the position of the reflective tapes.

Instrumented vehicle has been used in UK and France for the calibration of MS-WIM arrays within the OECD/DIVINE project in Abingdon (UK) with a 2-axle instrumented vehicle of the TRL, and in Trappes (RN10, France) with the 5/6-axle instrumented vehicle (semi-trailer) of the CNRC (Jacob & Dolcemascolo 1995, Huhtala and Jacob, 1995). No detailed reports have been published on those calibrations.

VTT has instrumented also later in autumn 1998 another vehicle, two-axle tractor with a semi-trailer with tridem axles. It has good quality air suspensions and thus its suspension is much better than that of the vehicle used in WAVE which has old steel suspensions. The newly instrumented vehicle is used in an international research project (Huhtala 1999b). In principle the system is the same but primarily shear strain gauges are used. They are less sensitive for transverse lateral forces and their place must be more carefully selected. Because WIM-stations are on straight parts of roads this is not very important.

4.3 Measurements at CET (Lulea)

The measurements were made at Lulea on 9 - 10 June 1997. Figure 9 shows an example of measured dynamic variations in the axle loads at the speed of 80 km/h over the test field at Lulea. It is typical that the dynamic axle loads of the steering axle are smaller than at the other axles and that the axle hop is small compared to the body bounce. Because the road is very smooth the dynamic axle loads are relatively small. Although body bounce is more important the axle hop is not negligible.

It can be seen, too that even if the test road is very smooth the dynamic axle loads are different along the road and thus some WIM-systems may have advantages or disadvantages compared to the others. Of course figures above are only examples and for final conclusions about the place of WIM-systems more measurements are needed. However, it can be seen that the increasing dynamic axle loads at 130 meters in Figure 9 are due to the very small unevenness in pavement after installation and repaving of the OWC WIM-system.

The effect of a specific unevenness can be compensated in certain cases as discussed in (Huhtala & al 1992) but here is no enough experience by the present time.

Please note that the Figure 9 is only an example. If the speed or vehicle is different the maxima and minima of the dynamic axle loads will be at different place and of different magnitude because the frequency of the dynamic axle load is independent of the speed. Both the magnitude and frequency are depending on the properties of the vehicle, too. Because the VTT test vehicle is old and it has steel suspensions both the frequencies and magnitudes are greater than in most vehicles driving at Lulea and Metz test areas. However, the general view is the same.

Figure 10 shows dynamic driving axle loads of three passes at 80 km/h on one WIM-system. First it can be noted that dynamic axle loads are fairly repetitive, all three passes are nearly the same. Secondly, the WIM-system, in this case a well-fitted PAT bending plate causes change in the dynamic axle load.

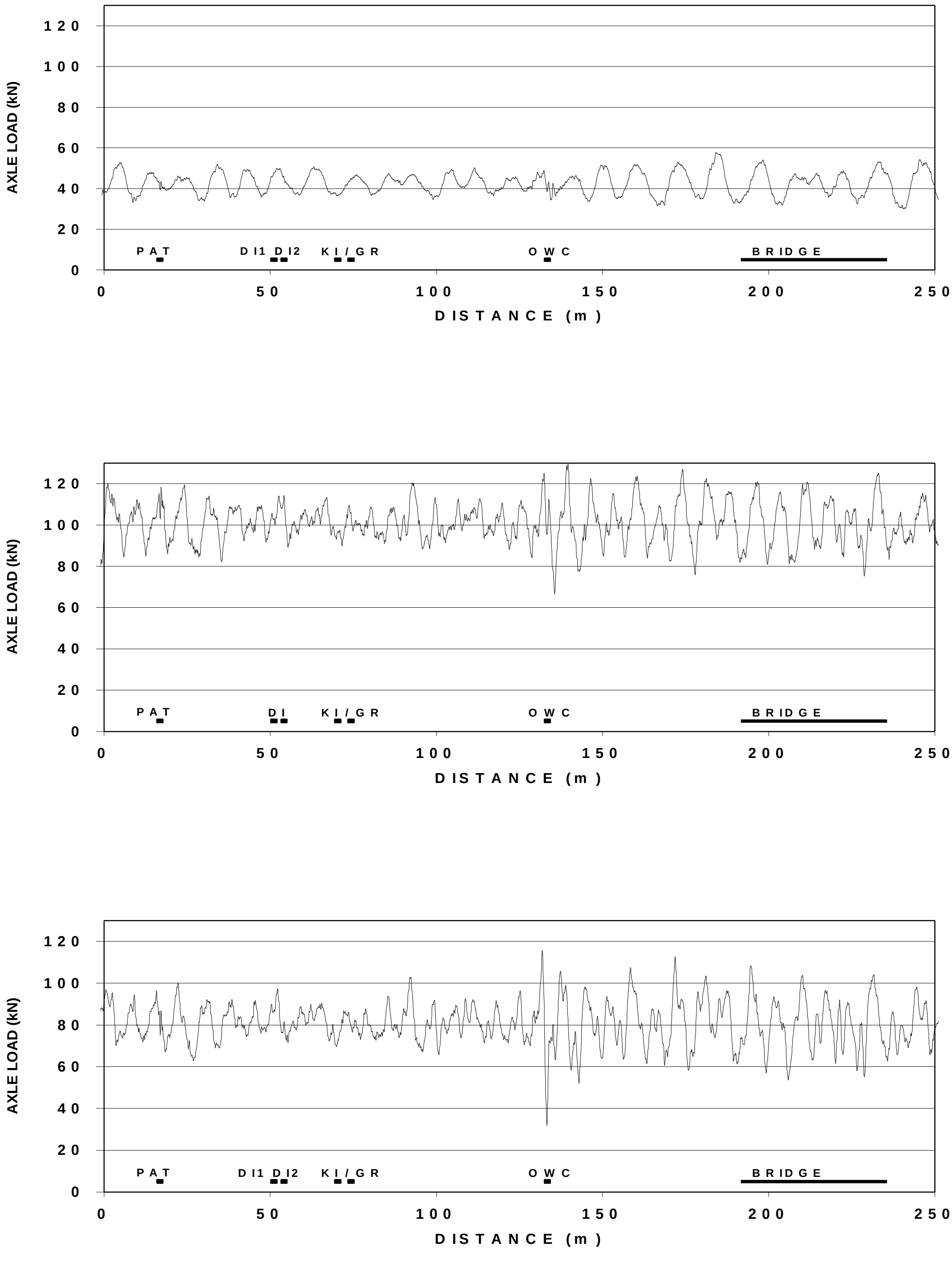


Figure 9 Example of dynamic axle loads at Lulea test site (front, drive and bogie axle).

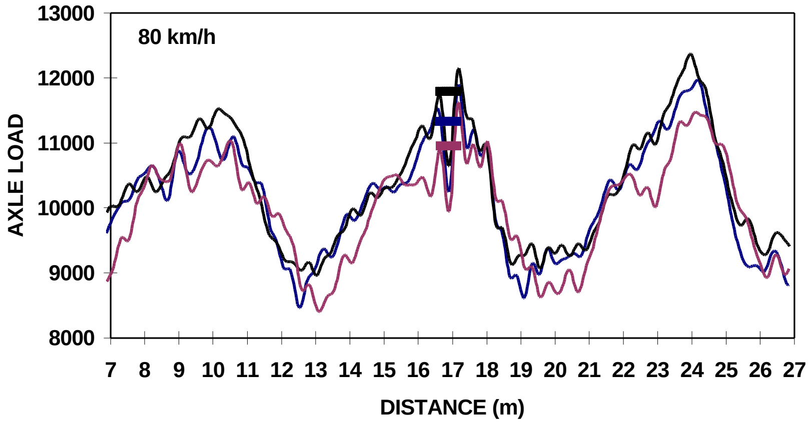


Figure 10 Dynamic axle loads of the driving axle over one WIM-system, three vehicle passes.

The horizontal bars show the position and the length of the bending plate and the axle loads measured by the WIM-system. The order of the corresponding WIM and dynamic axle loads are the same but the peak values of dynamic load measurements are smaller. However, if dynamic load on the bending plate is smoothed or the peak will not be taken into account, dynamic axle loads and WIM results fit very well. Perhaps the negative peak is typical and is taken into account in the calibration.

Please note, too that the tyre imprint has a length of about 0.3 meters.

Figure 11 shows dynamic steering axle loads at four speeds; 50, 60, 70 and 80 km/h. Because the speeds are different there is no repetitive dynamic loading. However, the small unevenness caused by the bending plate put all the dynamic axle loads in phase, which later dispenses. The same has been found in computer simulations (Huhtala & al 1992, Huhtala & al 1993, Huhtala & al 1994.

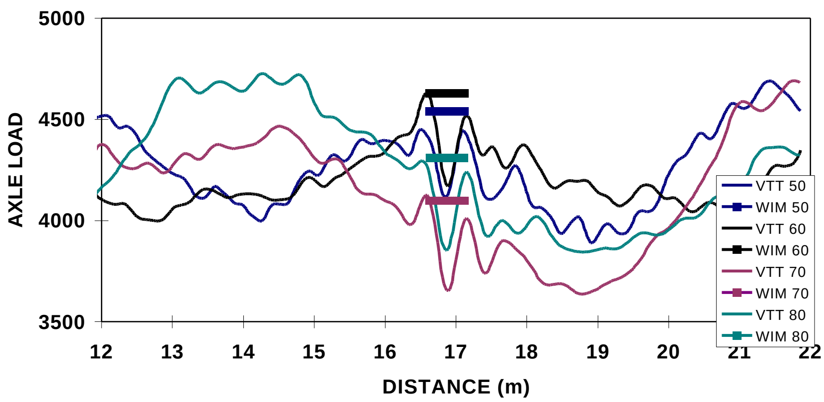


Figure 11 Dynamic axle loads of steering axle and corresponding WIM-measurements

As the horizontal bars which represent the WIM readings are compared to dynamic loads measured by the vehicle the values fit reasonably well in the same way as in Figure 10.

The same phenomenon is found in Figure 12 (driving tandem axle) and in Figure 13 (carrying bogie axle).

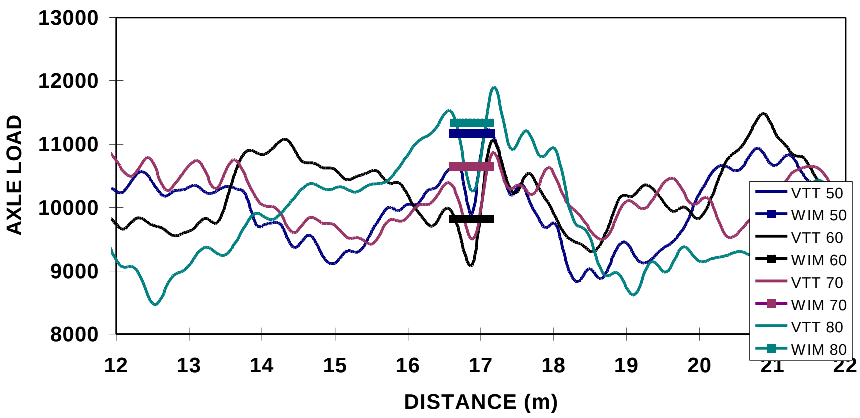


Figure 12 Dynamic axle loads of driving axle and corresponding WIM-measurements

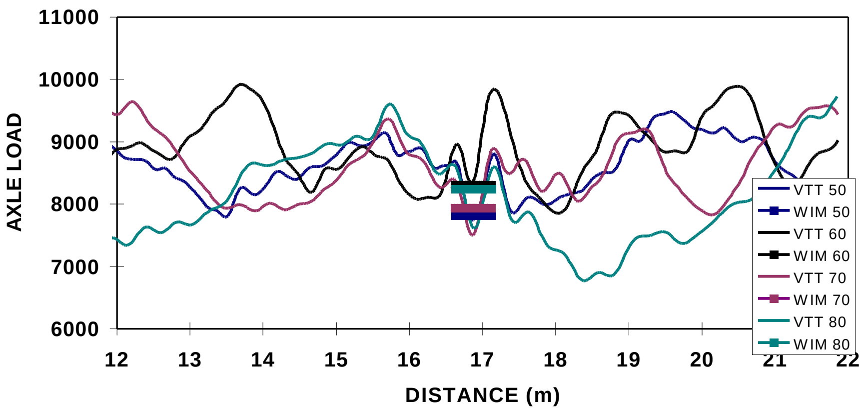


Figure 13 Dynamic axle loads of carrying bogie axle and corresponding WIM-measurements

This phenomenon may increase accuracy of a bending plate WIM-system. The WIM-system is calibrated at the site which may take into account how well the plate is embedded to the pavement and thus what is its effect on calibration. However, this phenomenon should be studied further with field tests and simulations.

All the points available from the data are presented in Figure 14. The axle load measured by the instrumented vehicle is on the abscissa and corresponding axle loads measured by the WIM-system are on the ordinate. The first group of points on the left (mainly between 2000 -

4000 kg) are front axle loads or empty bogie axle, the group on the right (mainly 9000 - 11000 kg) are the driving axle of the tandem axle and the group in the middle corresponding carrying (bogie) axle of the tandem axle. The driving axle carries about 55% of the whole tandem axle load in this vehicle type. The vehicle was driven with full load and empty and therefore there are also very low values for tandem axles. They are more scattered because suspensions are designed for full load and thus they do not work as well with small load.

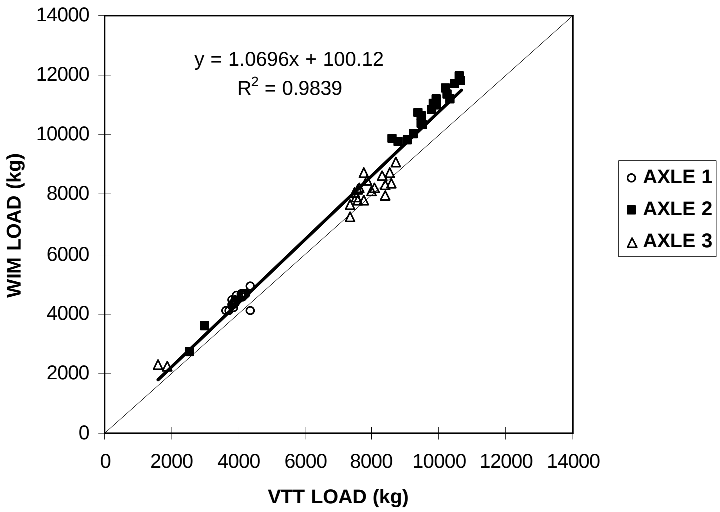


Figure 14 Dynamic axle loads measured in the vehicle (VTT) and by a WIM-system

Dynamic loads are different because four speeds were used. The points from the front axle and the points from the driving axe are reasonably nicely on a straight line but those from the running axle are more scattered. It may be due to the short recovery time of the sensor for tandem axle especially in this case as the distance between the tandem axles is only 1.20 m and thus the WIM-sensors give smaller axle load values for the latter axle.

The regression line deviates slightly from the 45-degree line and its coefficient is 1.07 or there is a systematic error of 7 %. The fit is quite good as the r^2 – value is 0.984. Regression lines were calculated for each axle and the coefficients are 1.104 for front axle, 1.109 for first tandem axle and 1.035 for second tandem axle.

Load coefficients (load from WIM divided by load with VTT measurement) are presented in Table 2

Table 2 Load coefficients axle by axle

Axle	Mean value	Standard Deviation
Axle 1	1.106	0.0446
Axle 2	1.111	0.0269
Axle 3	1.065	0.1074
All	1.094	0.0708

The scatter in Figure 14 is due to both the inaccuracy of the WIM-system and the inaccuracy of the dynamic axle load measurement. There are no means to know which part is due to inaccuracy of the WIM-system and which part is due to inaccuracy of the dynamic wheel load measurements.

As is seen in Figures 11 – 13 the dynamic axle load on the plate changes and is equivocal. Thus it is easily understandable that the points are not on the 45-degree line. It could be possible to define that kind of algorithm used in the dynamic axle load measurement or the length or the point which is taken as the load on the WIM-plate would be defined in order to get best fit to 45-degree line. It might be of little use because it probably depends on the site and on the tyre types of the vehicle.

Thus the deviation from the 45-degree line can be taken as error of neither WIM nor dynamic vehicle measurement systems.

The comparison could be made at Lulea only with the bending plate because only two WIM systems worked properly at the time as the measurements were made. The other system uses two piezo strip sensors in calculating the axle load. Kistler/Golden River worked also well during these measurements. It uses two sensor-lines four metres apart. Both sensor lines are separated electrically into left and right channels, thus each axle is measured four times. The two left and two right channels are compared and averaged. This system is used for detecting left/right differences for instance due to wind or at Lulea for identifying the vehicles passing the sensors outside the lane.

However, similar comparison of dynamic wheel loads and WIM measurements were at CMT (Metz) which are handled later in point “4.5.4 Coefficient value” and in chapter “6 Discussion”.

The mean value has no use for the comparison to dynamic loadings. Very much work would have been needed in order to get values separately and that was in practice impossible.

VTT vehicle could not be taken back to Lulea because of the distance from VTT and thus these measurements could not be repeated later.

4.4 Measurements at CMT (Metz)

The instrumented vehicle of VTT made measurements at A31 near Metz on 8 - 12 June 1998.

The test area consisted of the Obrion site (Figure 15) and Belleville and Autreville bridges. The Obrion Site included a multiple WIM sensor and several WIM-stations used in CMT test. The test site is described more in detail in point 5.2.1. and in reference Hallstrom & al 1999.

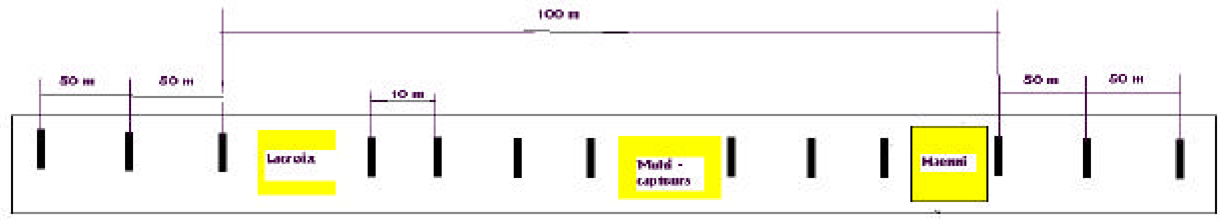


Figure 15 General plan of the Metz test site.

VTT made the measurements with the instrumented vehicle. All distance measurements and the installation of reflective tapes were performed by the French organisers of each test. The measured length was longer than originally planned and it may be the reason for difficulties in installing reflective tapes with good accuracy.

The profile of the test sections is presented in Figure 16. The first WIM-system is installed at the position 300 metres (see also Figure 17).

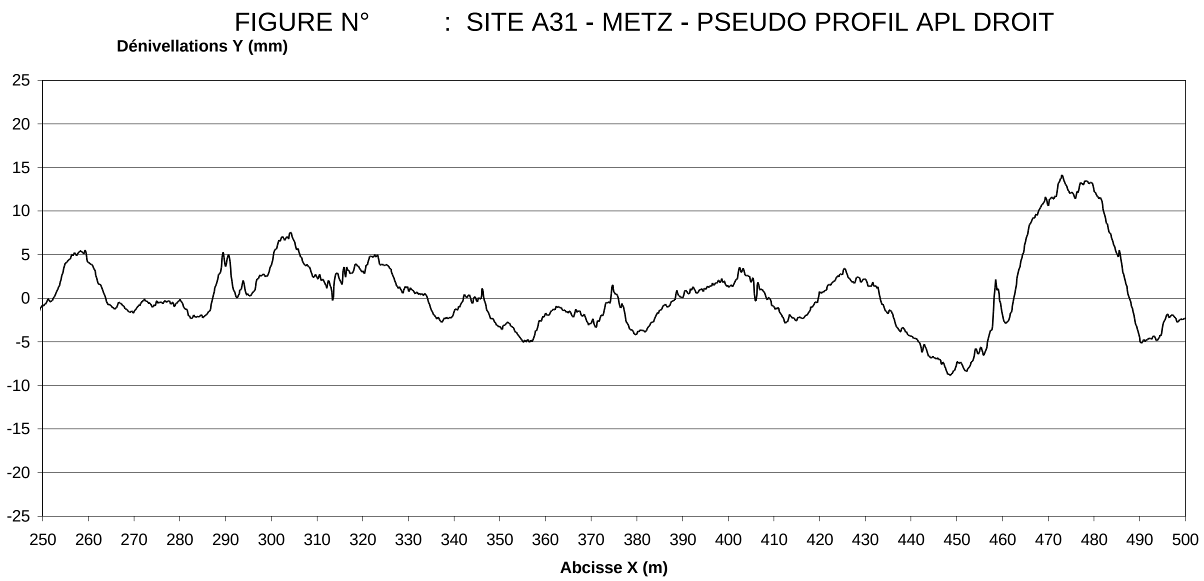


Figure 16 The profile of the test section, right wheel path.

A typical figure of dynamic loadings along the test area is presented in Figure 17. It can be seen that the road at Metz is about as even as at Lulea (Figure 9).

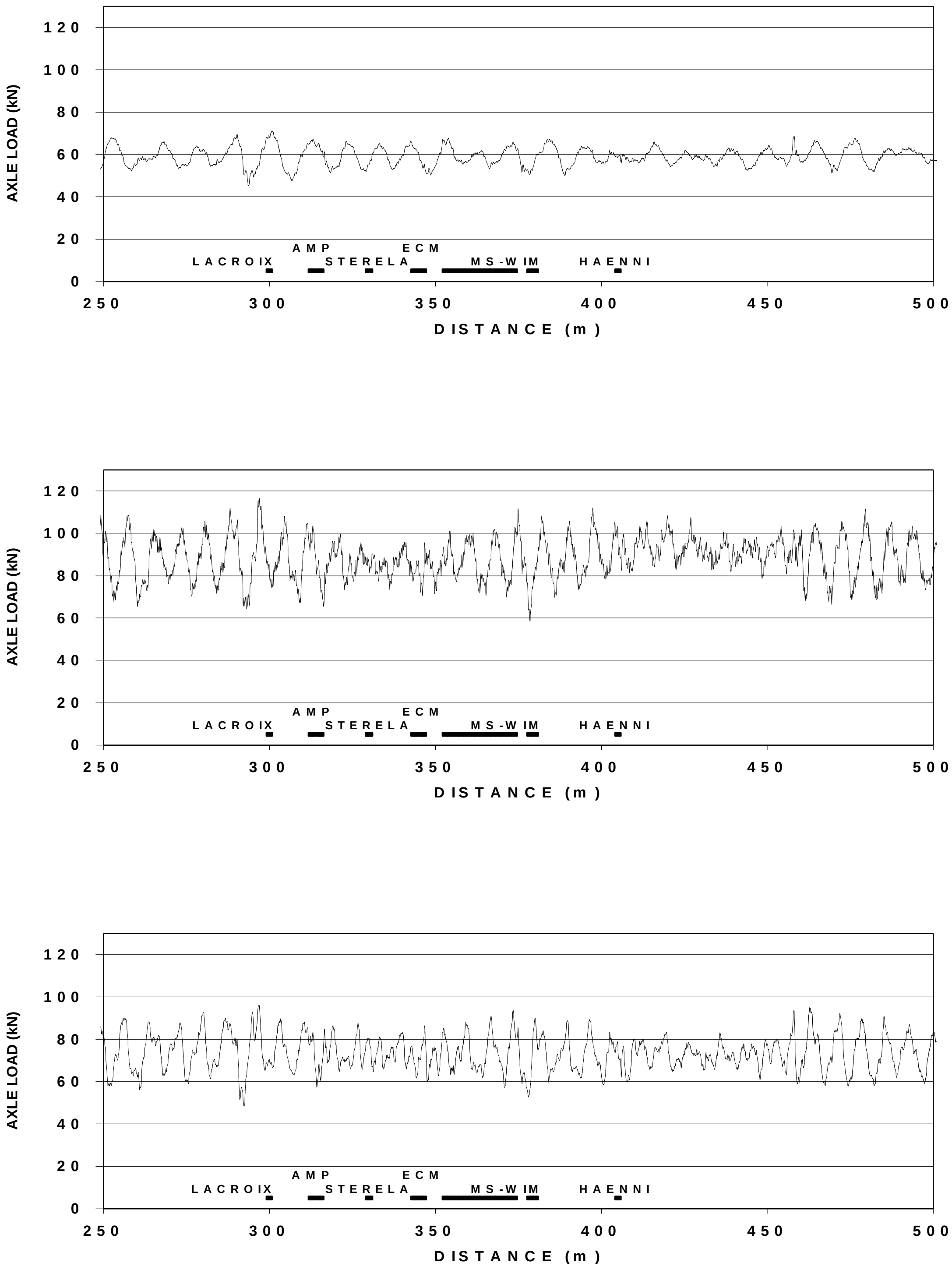


Figure 17 Example of dynamic axle loads at Metz test site (front, drive and bogie axle).

4.5 Multiple sensor WIM

4.5.1 Test site and measurements

In order to apply advanced method for the estimation of the static weight (WP1.1 – method of signal impact reconstruction), the bars of the multisensor WIM array have to make the measurement of the dynamic loading of the axle and not their static weight, as one generally tries to do in WIM operation. The aim is not to eliminate the effect of evenness on the dynamic loading.

So the calibration is an essential step and can only be perform with an instrumented vehicle able to make measurements of dynamic loading at each bar.

The site consists of 18 piezoceramics bars and the distance between each bar is 1.6m apart. They are numbered from –1 to 16 since bars 13 and 14 were not connected because these two bars had problems of sensibility (Figure 18).

The length array is 27.2 metres.

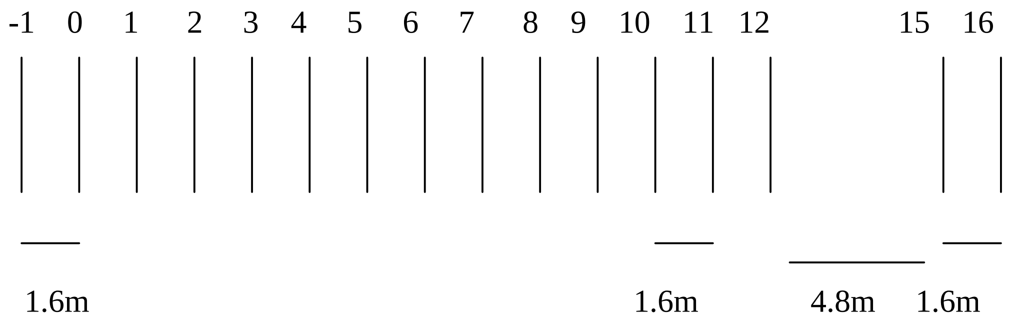


Figure 18. Layout of the MS-WIM array.

The APL is a car-towed device used to measure longitudinal profile in the short (SW), medium (MW) and long wavelengths (LW) respectively.

According to Table 3, the site is a class I site according the COST 323 specifications.

Table 3 Obrion's site characteristics compared to the tolerance of class 1.

Criteria	Radius of curvature (m)	Long. Slope	Transv. Slope	Rutting (mm)	Caracteristic deflection (1/100 mm)	Evenness (IRI) (mm/m)	Eveness (APL) (SW-MW-LW)
Tolerance of class 1	> 1000	≤ 2%	≤ 2%	≤ 4	≤ 15	≤ 1,3	≥ 9 - 9 – 9
Obrion site	> 1000	< 1%	1%	4	5	0,79	9 - 9 – 10

The dynamic loadings measured at the vehicle and at the WIM-sensors were matched. The system at the vehicle makes a measurement at each 22 mm (at the speed of 80 km/h) and thus the theoretical maximum error in spatial measurements may be that 22 mm. There were some inaccuracies in installing the reflecting tapes, which could be seen as the speed was measured using the distances between the tapes. The error may be up to 100 mm which means an error of 1 % as in most cases as the distance between the tapes were 10 m. The accumulating error has no importance because the speed and the exact position of the wheel was measured always from two nearest tapes.

The sensor is narrow and as the imprint of the tyre is longer. Thus the load should not be considered as a point load but little longer. It was decided after some trials that the corresponding dynamic axle load is the mean value measured within a 150 mm range.

The experiment took place between the 9 and the 12 of June 1998.

The VTT truck made 71 passes over 500 meters but 43 passes were recorded both by all the bars of the MS WIM array and then VTT truck.

Because the evenness of the road is very good, a bump was installed on the pavement and 23 passes were done with this bump.

The load configurations are shown in Table 4 and the number of passes by configuration of load/speed is given in Table 5.

Table 4 Load configurations of the VTT passes on the MS WIM array.

	Axle 1(kN)	**Axle 2 (kN)**	**Axle 3 (kN)**	**GW (kN)**
Fully loaded	58.8	86.2	72.2	217.2
Half loaded	57.8	60.3	48.8	166.9
Empty	51.2	35.8	25.5	112.5

Table 5 Plan of measurement of instrumented VTT truck (the passes are at 40, 60, 70 and 90 kph).

Date	**Load / Speed**
9-06-1998	Half loaded with bump / 4 – 4 – 2 - 0
10-06-1998	Half loaded/ 0 – 5 – 0 – 5 ; Empty/ 0 – 5 – 0 – 5
11-06-1998	Full/ 0 – 6 – 0 – 5; Full with bump/ 4 – 5 – 4 – 0
12-06-1998	Full loaded/ 0 – 4 – 0 – 4

Moreover, the deflectograph vehicle made 12 passes on the MSWIM array on 8 June 1998.

The principle of use of dynamic loading measurements can be seen in Figure 19. Dynamic wheel loads of both left and right wheel are presented in the figure. Corresponding values used in the calibration are marked with crosses and balls. Please note that only a small error in longitudinal measurements causes in many cases considerable error in measured dynamic wheel load.

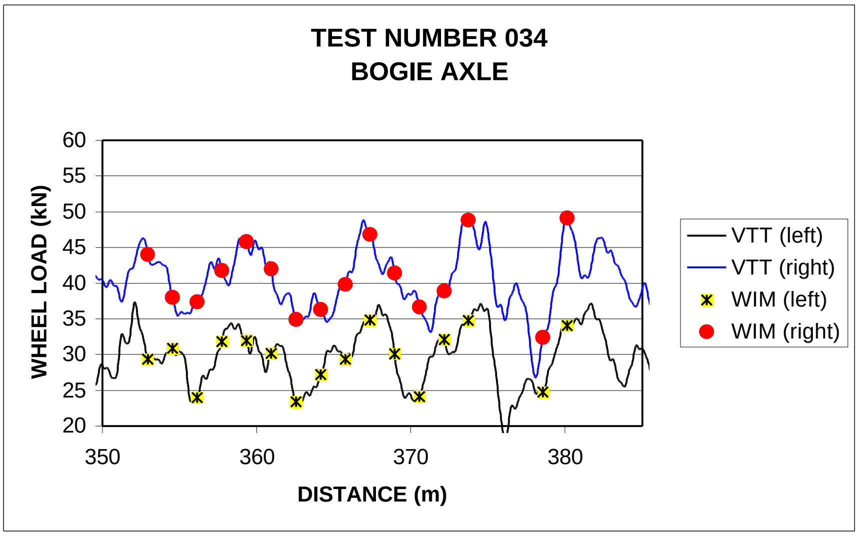


Figure 19 An example of dynamic axle loads and corresponding values used for the analysis.

4.5.2 Repeatability of the measurement provided by the bars and the impact force of the VTT truck

The repeatability coefficients of variation of the measurement were computed for each bar (for one load and one speed. For the worst case, the coefficient of variation for axle 1 is 4.7% (Half loaded-80km/h); 7,38% (Full loaded 80km/h) for axle 2 and 8.82% for axle 3 (Full loaded 80km/h). That means at the level of confidence of 95%, the maximum deviation of the measurement (i.e repeatability of the measurement) is 9.4% for axle 1, 14.6% for axle 2 and 17,6% for axle 3. These are, however, the measures of the repeatability of loads; not the measurements and do not tell anything about the accuracy of the measurement system.

4.5.3 Calibration

Sensor coefficients were defined for each bar and each pass (all passes were used except with bump or empty vehicle) as value measured by the instrumented vehicle divided by the value measured by the WIM-sensor. The mean values of coefficients by axles are presented in Figure 20 and corresponding standard deviations in Figure 21. The exact values are presented in Appendix 1.

Similar calculations were performed to determine the calibration coefficients for gross weight (computed by summing, for one given sensor, all the axle weight of one pass of the VTT truck), the tandem axle and all the axles.

Table 6 gives the calibration coefficient for each bar and computes whatever the speed and load.

The coefficients of variation, which indicate the dispersion of the calibration coefficient, are very high (between 4 and 18%).

It can be seen from Figure 20 and more in detail in appendix 1 that the front axle (axle 1) co-efficients are clearly greater than one (mean value 1.15) or dynamic axle load measurements give greater values than sensors. The values of the second tandem axle (axle 3) are also greater than one (mean value 1.13) and the values of the first tandem axle (driving axle) are smaller than one (mean value 0.94).

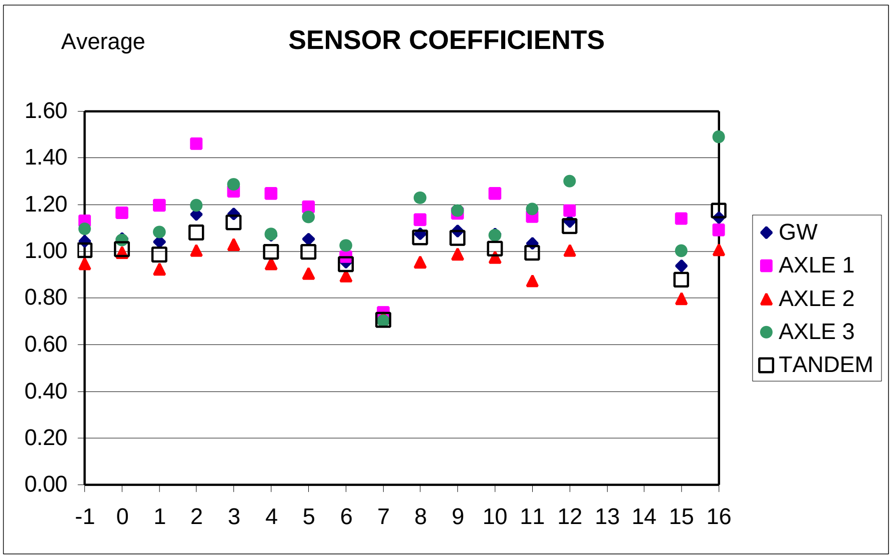


Figure 20 Sensor coefficients axle by axle, mean value of all passes but as the bump was used.

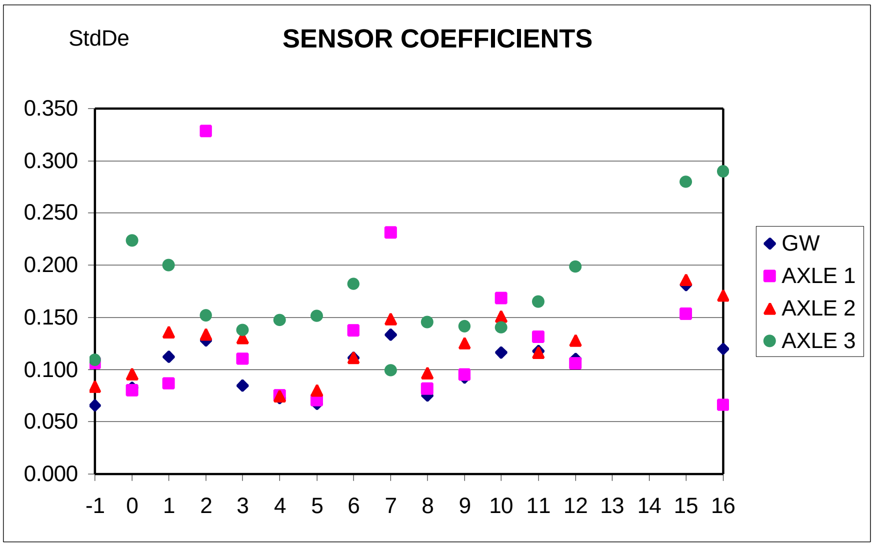


Figure 21 Standard deviations of sensor coefficients axle by axle, mean value of all passes but empty vehicle and as the bump was used.

Table 6 Statistics of the calibration coefficient (gross weight).

Bar	Calibration Coeff	Min Coeff	Max coeff	Coeff Var (Coeff dyn) %
-1	1,04	0,94	1,22	6,3
0	1,06	0,95	1,32	7,8
1	1,04	0,89	1,32	10,8
2	1,16	0,96	1,42	11,0
3	1,16	1,04	1,39	7,3
4	1,07	0,97	1,14	4,2
5	1,05	0,95	1,18	6,4
6	0,95	0,82	1,39	11,7
7	0,71	0,52	1,03	18,7
8	1,08	0,95	1,19	7,0
9	1,09	0,91	1,28	8,5
10	1,07	0,93	1,37	10,8
11	1,03	0,85	1,31	11,4
12	1,13	0,87	1,32	9,8
15	0,94	0,73	1,06	14,0
16	1,14	0,89	1,37	10,5

This kind of differences may be due to vehicle factors like

- torque because of driving power (makes front axle lighter)
- air resistance (complicated but probably makes front axle lighter)
- or due to WIM-measurement factors like
- sensors may give lower values for single tyres than for dual tyres
- calibration of the measurement system in the vehicle is not perfect
- longitudinal position measurements are not good enough.

These will be handled later in Chapter 6 Conclusions.

If the load and the speed are the same the spatial repeatability is good. Regression coefficients of front axles are over 0.90 and with full load all over 0.96. Corresponding values for second axle are with full load over 0.72 and for third axle 0.45.Thus it is important to vary speed and/or load in order to get loadings in different phases on the WIM-sensors. Load affects the dynamic properties of the suspensions which usually is designed especially for full load.

The bump excited greater dynamic loading and the coefficients were different. The results from the bump excited loading are more difficult to use or analyse because there are greater loadings on the first sensors than on later sensors. Therefore and because the dynamic loadings are big enough the coefficients after the bump were not analysed further (the coefficients were not so “good” as on normal loading).

The mean value of the axles in tandem is presented as squares in Figure 20. They are relatively close to one or the high values of third axle and low values of the second axle compensate each other.

The GW in Figure 20 is the mean value of all coefficients. They are also in Table 6. Those values should be used as calibration coefficients as it is not known the reason for the difference between first and other axles.

The coefficients vary from 0.71 to 1.16 and their mean value is 1.04. The coefficient of sensor 7 is clearly smaller than others.

4.5.4 Influence of the load

It was decided to study the influence of the load on calibration coefficient on 3 bars : bar n°5 the less scattered, bar n°7 the most scattered and bar N°10 which is in between.

The more scattered the repeatability measurement of the bar, the more influence of the load on the calibration coefficients. It can be seen that the load have a great influence on the calibration coefficient. Results on the sensor 5 (Figure 22) show that in most cases the calibration coefficient varies within ± 5%. Sensor 10, representing average figures, has the calibration coefficient mainly within ± 10%.

Due to very different behaviour shown in Figure 20, results on the sensor 7 are doubtful. In all cases the sensor gives about 70% of other sensor’s value.

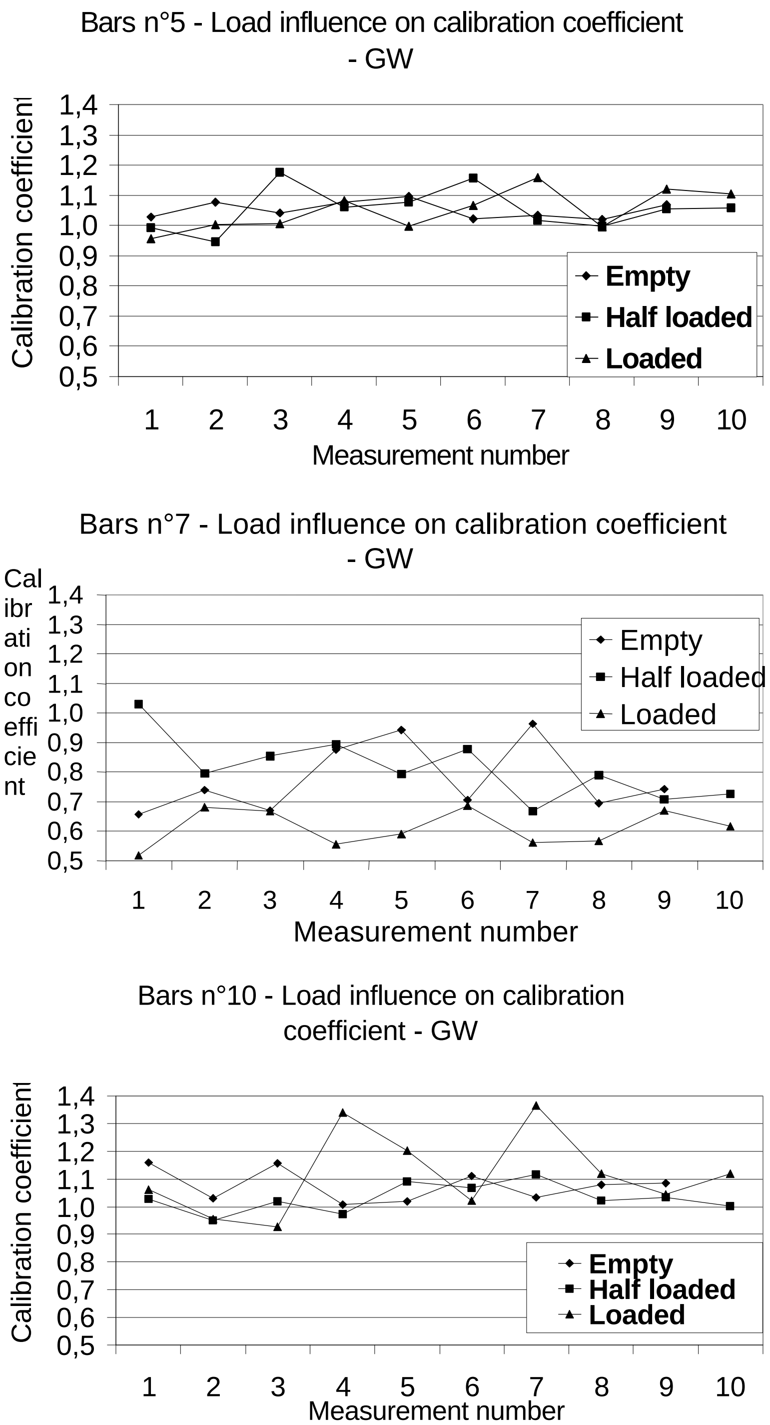


Figure 22 Influence of the load on the calibration coefficient for bar 5, 7 and 10 (All speed).

4.5.5 Influence of the speed

The more scattered the repeatability measurement of the bar (see Figure 23), the more influence of the speed on the calibration coefficients. It was found that, due to the age of the instrumented truck, running at higher speeds (90 km/h) dynamic axle load measurements were interfered by truck's own vibrations. These measurements should be perhaps ignored.

The results of the sensor 5 show most cases that calibration coefficient is within ± 5%. In worse case, with the sensor 10 calibration coefficients are kept within ± 10%. Due to same reason as in analysis on the influence of the load sensor 7 can be ignored.

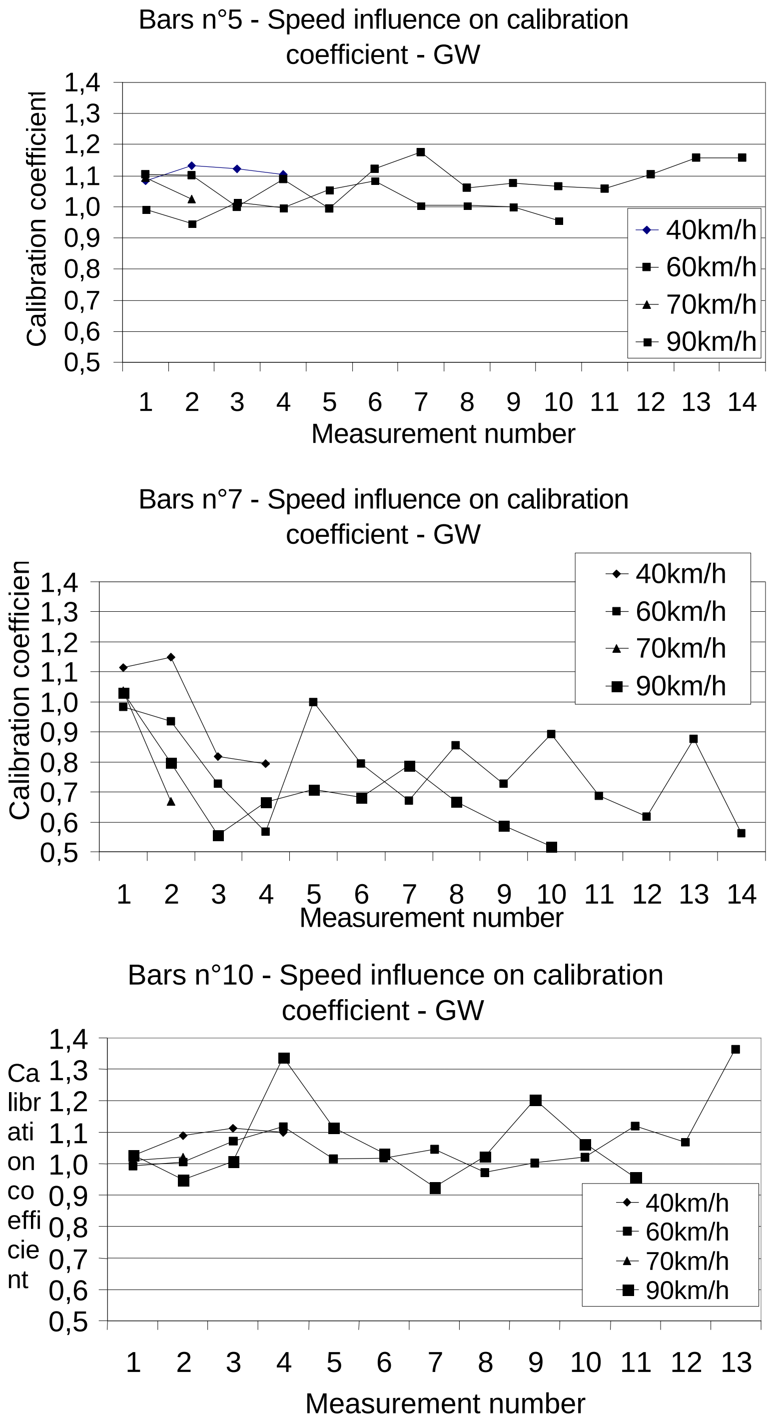


Figure 23 Influence of the speed on the calibration coefficient for bar 5, 7 and 10 (All load except empty).

4.5.6 Influence of the rank of the VTT truck

Figure 24 shows that the rank of the VTT truck has a great influence on the calibration coefficient. Usually, the gross weight calibration coefficient is chosen to be introduce in the WIM station. So, in this case, the measurement of impact force of an axle can differ from the expected force up to 40% because there can be a difference of 410% between the coefficient computed for single axle and the gross weight.

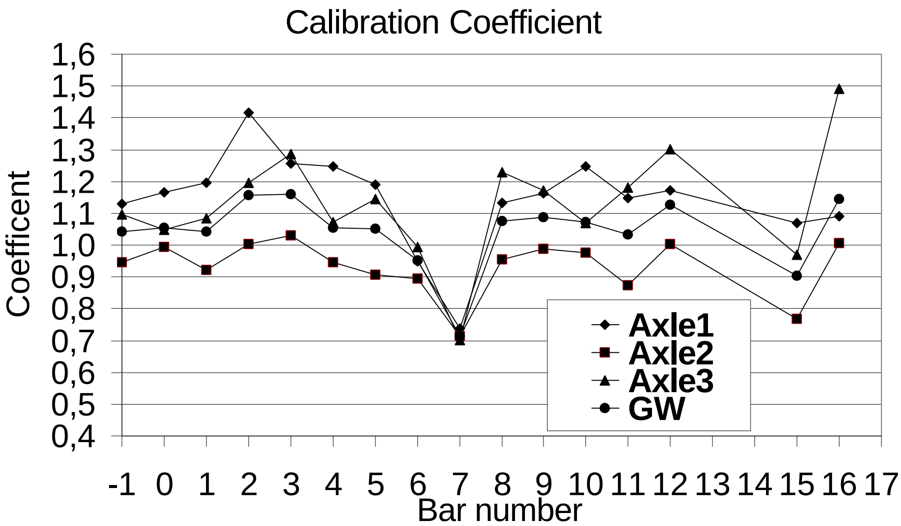


Figure 24 Influence of the rank on the calibration coefficient (all load except empty and speed).

It can be seen that, excepted for bar 7, the measurement from axle 2 are always over estimate while those from axle 1, 3 and gross weight are systematically under estimate (?).

Bar n°7 seems to have problem of sensitivity because the corresponding calibration coefficient is very different from the others and the coefficient of variation of the calibration coefficient of this bar (see table 4) is very high (17%).

4.5.7 Influence of the type of truck

Figure 25 shows the calibration coefficient for the VTT truck and the deflectograph vehicle (for the deflectograph vehicle, the static weight is taken as a reference value for the computation of the calibration coefficient).

The figure shows that there can be, for a given bar, a difference of 20% between these two calibration coefficients. This is very high and two times higher than the difference computed with the MS WIM array of Trappes (with the measurement of CNRC truck and deflectograph vehicle).

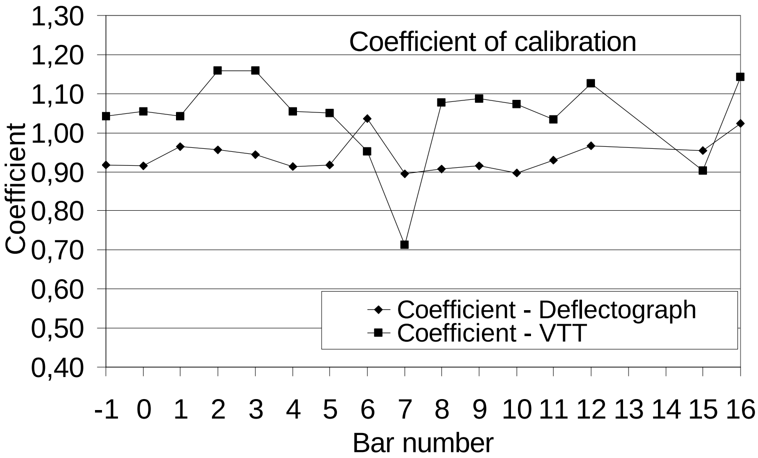


Figure 25 Influence of the type of truck on the calibration coefficient of Gross Weight.

This figure indicates that the calibration coefficient, to introduce to the WIM station, depends on the type of vehicle.

Standard deviations of the coefficient at CMT (Metz) are typically about 10 percent for front tyres (exceptions sensors 2 and 7), about 13 percent for the second axle and more than 15 percent for the third axle (exception sensors 15 and 16).

LCPC made a spectral analysis of the dynamic load measurements made at Metz. Axle bounce frequency was found to be 2.5 Hz, which is the same as in Table 1 measured by VTT:

5. CALIBRATION BY AXLE RANK

5.1 Introduction

A number of factors influence the accuracy of static load estimation by weigh-in-motion and may induce some load transfer from axle to axle, or some bias to the axle loads:

- the driving torque,
- the aerodynamic forces applied to the vehicle,
- tyre types (single, dual),
- tyre width,
- size of tyre imprint
- tyre inflation pressure,
- the local pavement deflection and evenness,
- sensor response and its shape with respect to time or its extension in the traffic direction.

Among these factors, some are related to the vehicle and its driving conditions, others to the road, and the last ones to the WIM sensor and system. Moreover, the vehicle motions are mainly induced by the road profile. For a given WIM system, installed on a road, it is expected that some of these effects are repeatable, if related to the pavement and sensor. In such a case, an appropriate calibration could improve the static weight estimation.

Data collected by several WIM systems using different sensor technologies, on two different sites, were analysed. The influence of static axle load, speed, pavement temperature and axle spacing on the load estimation was analysed. If precisely known, the influence of these parameters could be corrected on real time and on-site by an automatic self-calibration procedure. Then the bias by axle rank was investigated with respect to static loads. Finally, based on the experimental findings, some bias corrections by axle rank have been proposed, and applied on data samples in order to verify the possible accuracy improvement.

5.2 Experiments

5.2.1 Continental Motorway Test (CMT)

The Continental Motorway Test belongs to the European Test Programme (ETP) of the COST 323 action but was used for WAVE-project, too. It was carried out on the A31 motorway, in the North-East of France, at the Obrion site. The site and traffic characteristics, the test plan and the main results are presented by (Stancyk and Jacob, 1999). The site is excellent for WIM, in class I of the European specification (COST323, 1997). Six marketed WIM systems were installed on the Obrion site (Table 7). The difference between systems N°5 and 6 is the layout of the WIM sensors with respect to the inductive loop (sensors outside or inside the loop).

Table 7 Systems tested in the CMT (Metz-Obrion)

N°	**Manufacturers**	**load sensor(s)**	**detection sensor(s)**	**Electronics**
1	HAENNI (CH)	1 capacitive mat	2 inductive loops	Racktel 8000
2	LACROIX (FR)	1 piezoceramic bar	2 inductive loops	SIREDO –LT1C
3	STERELA (FR)	1 piezoceramic nude cable ∅ 8 mm	2 inductive loops	SIREDO – Dac 871
4	STERELA (FR)	Ditto	4 magnetic sensors	ditto
5	ECM (FR)	2 piezoceramic bars	1 inductive loop	Hestia P
6	ECM (FR)	Ditto	Ditto	ditto

5.2.2 SIREDO Acceptance Test

The WIM systems selected for the National SIREDO WIM network (Rambeau et al., 1998) had to be tested for approval and system certification. This test was carried out on a slow lane of the motorway A75, near Saint-Flour in the centre of France, south of Clermont-Ferrand. The site is also excellent, in class I, with similar characteristics than in Obrion; the mean deflection was $9*10^{-2}$ mm. The traffic flow is 10,000 vehicles per day including 1,000 lorries.

Three WIM systems were installed in 1996 (Table 8). The Lacroix system was identical to the system N°2 of the CMT. The Sterela system in Saint-Flour used one fibre glass reinforced piezoceramic bar, as the Lacroix system, instead of two nude Vibracoax cables in the CMT.

Table 8 TaSIREDO systems tested in Saint-Flour (A75)

Manufacturers	**load sensor(s)**	**detection sensor(s)**	**Electronics**
LACROIX	1 piezo-ceramic bar with fibreglass (‘Transfibre’)	2 inductive loops	SIREDO –LT1C
STERELA	ditto	ditto	SIREDO – DAC 871
SIAT/SOFRELA	ditto	ditto	SIREDO – LT1C

In both tests, all the piezoceramic sensor systems used an automatic self-calibration procedure (Stanczyk, 1984, 1991). The manufacturers of systems N°1, 5 and 6 of the CMT reported that they already implemented a correction by axle rank by software. Therefore, the analysis will better evaluate the efficiency of these corrections than the intrinsic bias by axle rank.

5.3 Data Analysis

First the effect of various parameters on the error of static load estimation was analysed. Then, the mean bias on static axle load estimation by axle rank was analysed exhaustively for the 2-axle trucks (denoted C2) and the six systems of the CMT. The influence of the following parameters was investigated:

- total weight, greater or lower than 10 tons,
- axle load,
- vehicle speed; that is of particular interest, because most systems (those using strip/bar sensors) take the speed into account in the signal processing for load calculation,
- temperature; the temperature variations induce some changes of the pavement modulus, and thus of the mean deflection. On the other hand, the automatic self-calibration procedure used by the piezoceramic systems should in principle eliminate the temperature effects on the sensor response,
- axle spacing.

For three other vehicle categories (tractor with trailer, articulated semi-trailer trucks T2S2 and T2S3), the mean bias was analysed by axle rank for all the systems on both sites.

In order to eliminate the effect of system miscalibration and to focus on the bias by axle rank, the relative errors on axle loads have been multiplied for each vehicle by a factor Ws/Wd, where Ws is the reference static gross weight and Wd is the sum of all the axle loads measured by the WIM system for this vehicle. In such a way, the bias on the total weight is eliminated for each vehicle. The remaining mean bias on axle load becomes independent on the system calibration.

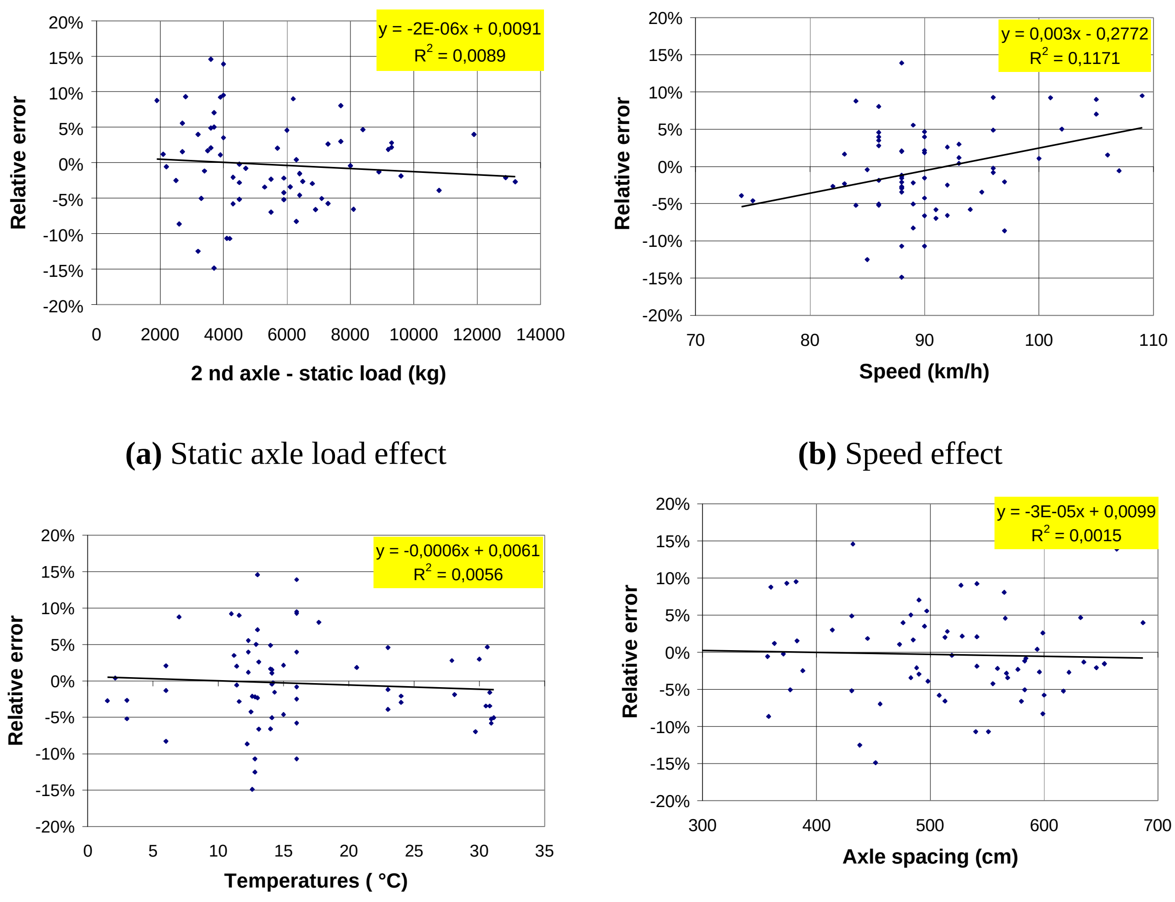
5.4 Results

5.4.1 Influence of Axle Loads, Vehicle Speed, Temperature and Axle Spacing

The data of the CMT are used here. The influence of static axle loads, vehicle speed, temperature and axle spacing on the axle load estimation (relative error) was analysed for each of the six WIM systems. Only the two-axle rigid trucks were considered.

Figure 26 shows the relative errors on the drive axle (2^{nd}), for the system N°2 (Lacroix), plotted versus the above listed parameters. In each case, a linear regression was performed. The regression coefficient R^2 is given. For the steer axles, the relative errors would be slightly larger while the static loads are smaller; because the total weights were corrected to be unbiased (section 3), the slopes of the regression lines for the steer axles would be of the other sign and inversely proportional to the ratio of the static axle loads. The neutral hypothesis is that the relative error is independent on the parameter, i.e. $R^2=0$ and the ideal regression line would be y=0 (unbiased system). The system is almost insensitive to all the four parameters, except to the speed: the higher the speed, the more the load transfer from the steer to the drive axle. That may be due to aerodynamic and driving torque effects.

In most cases, the regression coefficient R^2 was less than 0.2 for the six systems and the four parameters. Thus, the relative error on the axle load is rather independent on the four listed parameters. Some light slopes were found sometime with the systems 1, 5 and 6, but as explained below, that is generally an effect of a poor axle rank calibration already applied by software.



(a) Static axle load effect

(b) Speed effect

(c) Temperature effect

(d) Axle spacing effect

Figure 26 Correlation of the relative error on axle load with four parameters (System 2)

5.4.2 Biases by Axle Rank for each Vehicle Category (CMT)

For each system on CMT site, the biases by axle rank have been analysed for four vehicles categories (Figures 27-31).

For the two-axle rigid trucks, the mean biases depend on the system (Figure 27). For systems 3 to 6, the first axle is under-weighed compared to the second. However, the mean biases are rather low except for systems 5 and 6. A correction by axle rank was already implemented in these two systems, but was wrongly calibrated; therefore, the biases by axle rank were amplified instead of being eliminated. The correction consisted to transfer some load from the steer (first) axle to the drive (second) axle, or partly to the drive and to the bogie (axle 3 to 5) for the articulated semi-trailers T2S2 and T2S3. For these two systems, it is not possible to come back to the raw measures, and thus it is difficult to comment the results.

Figure 28 shows the biases by axle rank for two axle rigid trucks, split into those with a total weight over 10 t and those with a total weight under 10 t. For the systems 1 to 4, the mean bias depends on the total weight. For systems N°1 and 2, the heavier the truck the larger the bias, whereas for the systems N°3 and 4 the biases decrease for heavier vehicles.

In most cases, the absolute values of the mean bias are smaller than the standard deviations.

For the two-axle rigid trucks with a two axle trailer (Figure 29), the axle load biases are very low for system 2 as for the 2 axle trucks. For the system 1, the biases by axle rank have the same sign than with the two axle trucks, but with larger amplitudes. For all the other systems, the mean biases have the same sign for the first two axles with the 2 axle rigid trucks and the tractors with trailers. The third axle (first of the trailer) always has an important negative bias (>3%).

With the articulated trucks, two-axle tractor with a semi-trailer equipped with a tandem, all the systems using piezoceramic sensors show a negative bias on the steer axle and a positive bias on the drive axle of the tractor (Figures 29 and 30). The four systems N°1 to 4 give a negative bias for the first axle of the bogie. The tandem has a negative bias for the three first systems and a positive bias for the three last ones.

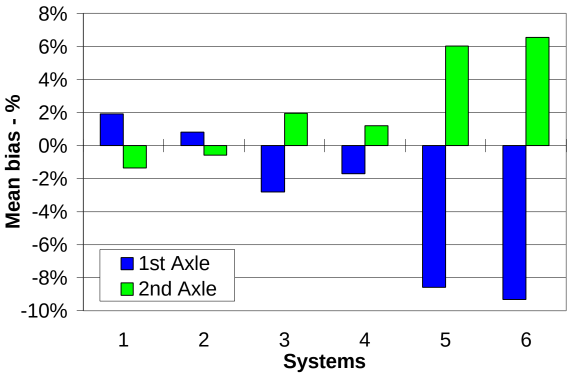


Figure 27 Mean bias by axle rank (2 axle trucks)

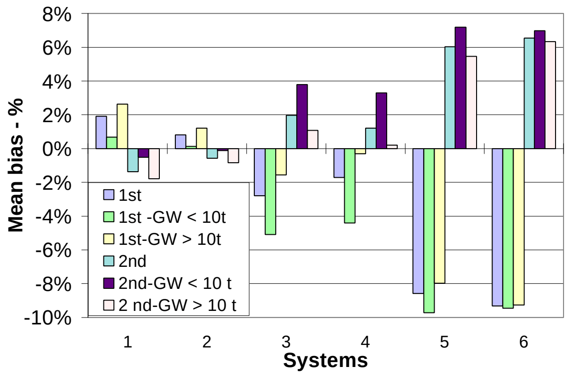


Figure 28 Mean bias by axle rank depending on the GW (2 axle trucks)

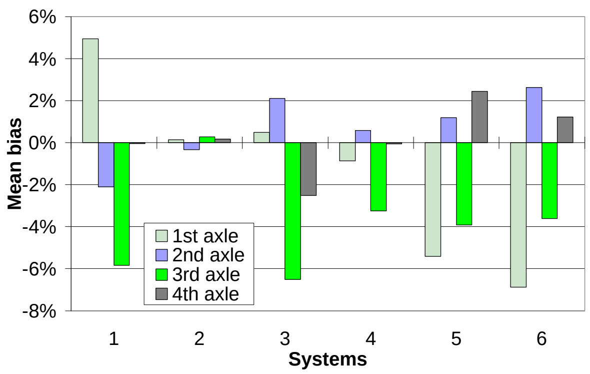


Figure 29 2 axle tractor with 2 axle trailer

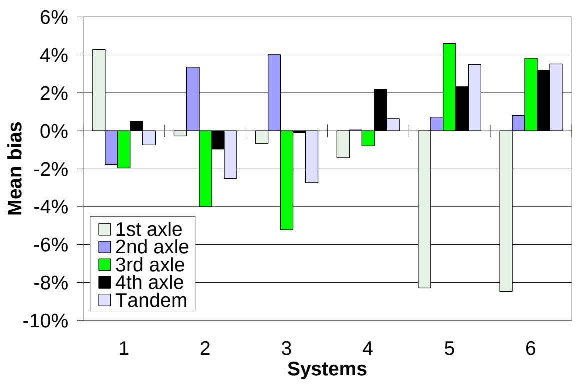


Figure 30 Articulated trucks with tandem

For articulated trucks with a semi-trailer equipped with a tridem axle (Figure 31), the biases are different from one system to another. The biases by axle rank are different than for the T2S2.

From these results, it can be concluded that the systems using piezoceramic sensors generally under-weigh the steer axle (N°1), while the drive axle (N°2) is over-weighed; the third axle is mostly under-weighed. In the tridem bogies, the first axle is always under-weighed compared to the second one, which is also under-weighed compared to the third one. However, there is no obvious law governing the mean bias by axle rank.

For the capacitive scale system (N°1), the load transfer seems always to be from the first axle to the other axles and axles groups. This system is the only one to provide the same biases by axle rank for the four trucks categories (Figure 32). However, this system is equipped with a correction by axle rank procedure. The first axle load is increased by a factor 1.07, in order to compensate its under-weighing. Thus, it can be estimated that the system, before correction, would under-weigh the steer axles by 3 to 5%, depending on the truck category.

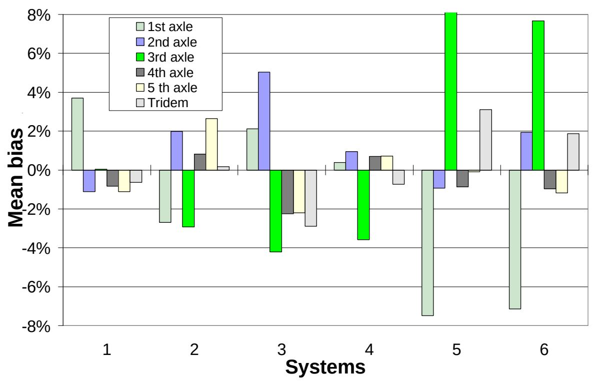


Figure 31 Articulated trucks with tridem

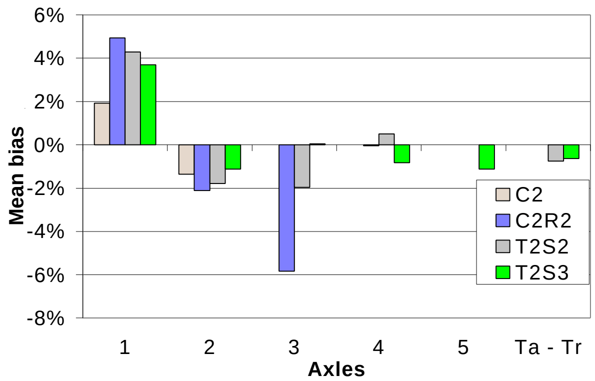


Figure 32 System 1 (capacitive scale)

Finally, all the systems without correction by axle rank, under-weigh the first axles. This may be due to an aerodynamic and a torque effect.

5.4.3 Biases by Axle Rank for each Vehicle Category (Saint Flour Test)

On the Saint Flour site, the biases are more important than those observed on the CMT site. Theses biases have the same sign for the three first axles, for all the trucks and the three systems. Thus, it can be concluded that systems using the same type of sensor and the same mounting, present biases varying in the same way (Figures 33 and 34).

On the data of this site, a constant load transfer of 3% is observed from the first axle to the second axle, and another 4% from the third axle to the last axles (Figure 33).

The Lacroix system was tested on the two sites. The sensors, their installation and the electronics were identical and in agreement with SIREDO standards. The biases by axle rank on the two site for all trucks are identical, with twice higher amplitudes on the Saint Flour site than on the CMT site. This is perhaps an effect of the pavement deflection, which is higher in St Flour (all the other conditions are almost the same). It is possible that the first axle acting on a strip sensor also induces a local bending of the pavement around the sensor, that reduces the sensor output, while the next axles, if shortly spaced, hit the sensors before the full pavement relaxation. This phenomenon could explain the load transfer from the first to the second and third axles in the bogies, but also for the short 2 axle tractors and rigid trucks.

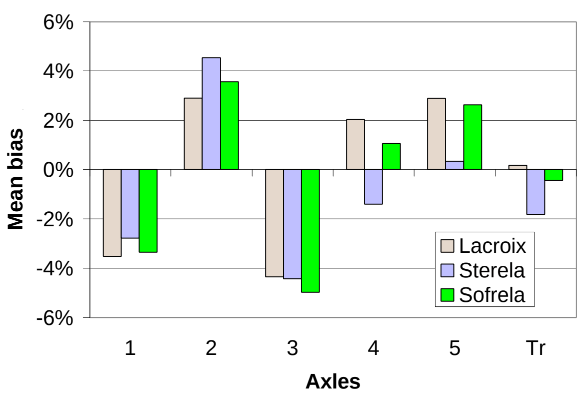


Figure 33 Biases by axle rank for 3 systems (St Flour)

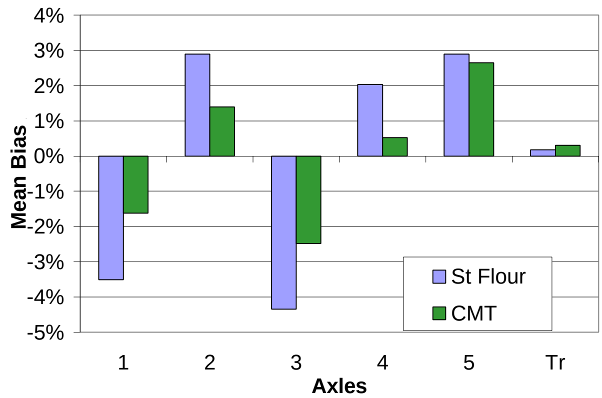


Figure 34 Biases by axle rank, Lacroix (St Flour and CMT)

5.5 Proposed Corrections by Axle Rank and Simulation

5.5.1 Corrections by Axle Rank

For the three systems already equipped of axle rank bias correction procedures (N°1, 5 and 6), the conclusions are that these procedures must be revised.

For the system N°1 (capacitive scale), the correction coefficient 1.07 applied on the first axle is too high, and should be reduced to 1.03 to 1.05, depending on the truck category. It seems that 1.05 would be convenient for the 2-axle rigid trucks, and 1.03 for the other trucks, at least on the CMT site. Doing that, the following axles would have a slightly lower negative bias, or even a low positive bias.

For the systems N°5 and 6, the correction already applied is not precisely known. But, too much load (6 to 8% in excess) is transferred by software from the steer axle to the drive axle and the bogie for the articulated trucks (T2S2 and T2S3). Without the detailed information on the current correction it is impossible to make anymore recommendation.

The systems N°3 and 4 have the highest scattering and are the lower accurate; thus we will not discuss furthermore any axle rank calibration procedure for them.

The system N°2 was the only one to be installed with the same sensors and electronics on two test sites. Therefore, the consistent conclusions drawn from both series of data may be used to propose a correction by axle rank.

The main objective of the correction by axle rank is to remove or reduce the mean observed bias. According to the previous remarks, a preliminary procedure could consist to:

- transfer some load from the drive axle to the steer axle,
- transfer some load from the second (and third) axles to the first axle of the bogies.

The 2 axle trucks with 2 axle trailer are not concerned, while they do not present any significant bias by axle rank.

The general equations to be implemented on the raw data may be written as:

for the 2 axle rigid trucks (C2):

$$Pt = Pe_1(1+k_1) + (Pe_2 - k_1 Pe_1) \tag{1}$$

for the 4 axle articulated trucks with a tandem under the semi-trailer (T2S2):

$$Pt = Pe_1(1+k_2) + (Pe_2 - k_2 Pe_1) + (Pe_3(1+k_3)) + (Pe_4 - k_3 Pe_3) \tag{2}$$

for the 5 axle articulated trucks with a tridem under the semi-trailer (T2S3):

$$Pt = Pe_1(1+k_2) + (Pe_2 - k_2 Pe_1) + (Pe_3(1+k_3)) + (Pe_4 - qk_3 Pe_3) + (Pe_5 - (1-q)k_3 Pe_3) \tag{3}$$

where: Pt and Pe_i are the total weight and the axle loads of the vehicle measured by the WIM system,

k_i are the proportions of axle load to be transferred from an axle to other axles, depending on the axle rank,

and q is a coefficient between 0 and 1.

Numerical values of k_i and q were derived from the data collected by the Lacroix systems on both sites (CMT and Saint Flour). Half of the vehicles were used to calibrate these coefficients, while the other half of the sample was used to assess the accuracy improvement resulting from this procedure (section 5.2). The numerical values proposed are:

for Saint Flour: k_1=0.03, k_2=0.03, k_3=0.04, and q=0.375;

for the CMT: k_1=0.01, k_2=0.03, k_3=0.03, and q=0.

5.5.2 Validation of the Calibration by Axle Rank by Simulation

Equations (1) to (3) and the numerical values proposed in section 5.1 were applied on the second half sample of data gathered on both test sites by the Lacroix systems, and not used to derive the coefficients, in order to provide 'corrected' data, axle by axle and vehicle by vehicle. Then, using these corrected data, the accuracy calculation was performed according to the European specification COST 323, and the results were compared to those before recalibration.

Table 9 presents the results for the Saint Flour data and table 10 those for the CMT data. In both cases, a slight accuracy improvement is shown for single axles and axles of a group. The δ_{min}, which represents the smallest confidence interval width with the specified level of confidence π_0 for the test conditions, is reduced by 1.1 for both criteria in Saint Flour, and by 0.4 and 0.6 respectively for these two criteria in the CMT. Moreover, in Saint Flour, the group of axle accuracy is slightly improved, with a δ_{min} reduced by 0.5. If the standard δ values of the tolerances are used for each criterion and the accepted accuracy classes, the levels of confidence π are increased by approximately 1%.

The accuracy classes are not modified, because of the small reduction of δ_{min}. However, these results are promising because the axle rank procedure seems to be rather robust and improve systematically the accuracy.

Table 9 St Flour - Lacroix system accuracy (I-R2)

		Statistics of relative errors			Accuracy calculation				
Before correction	**Number**	**Mean**	**St. dev.**	p_o	**Class**	d	d_{min}	p	**Class**
Criterion		(%)	(%)	(%)		(%)	(%)	(%)	**retained**
Single axle	66	-6.34	7.73	92.1	**C(15)**	20	19.3	93.2	
Axle of a group	48	-2.02	10.89	91.3	**C(15)**	25	22.5	94.6	
Group of axles	17	-1.27	8.84	86.3	**D+(20)**	23	18.5	94.5	**D+(20)**
Gross weight	33	-5.1	5.23	90.0	**C(15)**	15	13.8	93.2	
After correction	**Number**	**Mean**	**St. dev.**	p_o	**Class**	d	d_{min}	p	**Class**
Criterion		(%)	(%)	(%)		(%)	(%)	(%)	**retained**
Single axle	66	-6.09	7.19	92.1	**C(15)**	20	18.2	95.1	
axle of a group	48	-2.57	10.27	91.3	**C(15)**	25	21.4	95.7	
group of axles	17	-1.7	8.55	86.3	**D+(20)**	23	18.0	95.2	**D+(20)**
gross weight	33	-5.1	5.23	90.0	**C(15)**	15	13.8	93.2	

Table 10 CMT - Lacroix system accuracy (II-R2)

		Statistics of relative errors			Accuracy calculation				
Before correction	**Number**	**Mean**	**St. dev.**	p_o	**Class**	d	d_{min}	p	**Class**
Criterion		(%)	(%)	(%)		(%)	(%)	(%)	**retained**
single axle	240	1.44	7.70	92.5	**B(10)**	15	15.0	92.5	
axle of a group	296	0.25	10.45	92.7	**B(10)**	20	20.0	92.7	
group of axles	101	0.19	8.43	91.2	**C(15)**	18	16.2	94.4	**D+(20)**
gross weight	120	0.93	6.77	91.5	**C(15)**	15	13.1	95.4	

After correction	**Number**	**Mean**	**St. dev.**	p_o	**Class**	d	d_{min}	p	**Class**
Criterion		(%)	(%)	(%)		(%)	(%)	(%)	**retained**
single axle	240	1.83	7.42	92.5	**B(10)**	15	14.6	93.3	
axle of a group	296	0.25	10.15	92.7	**B(10)**	20	19.4	93.5	
group of axles	101	0.19	8.43	91.2	**C(15)**	18	16.2	94.4	**D+(20)**
gross weight	120	0.93	6.77	91.5	**C(15)**	15	13.1	95.4	

Finally, for aggressivity calculations (pavement fatigue), the bias is reduced significantly if the axle rank calibration procedure is used. With the data used for tables 8 and 9, the bias on the aggressivity is reduced from 12 to 6% (flexible pavement, α=5), and from 50 to 30% for semi-rigid pavement (α=12).

5.6 Conclusions

The calibration by axle rank provides promising results. Systematic biases were found for many WIM systems on various sites, for some axles of the trucks weighed in motion. These biases depend on the axle ranks, and may be partially explained by phenomena due to the pavement conditions, to the dynamics of the vehicles and to the sensors behaviour.

A calibration by axle rank can remove or reduce these bias, and thus improve the WIM accuracy for static weights and loads estimation. That is important for high accurate systems required for legal applications (Jacob and Stanczyk, 1999), but also for pavement engineering and accurate aggressivity calculations.

These preliminary results still have to be verified on a larger scale, with more test data. It is expected that in some circumstances, one accuracy class may be gained using this procedure. The procedure is easy to implement, either in a self-calibration algorithm or as a specific algorithm for the WIM systems which do not use any self-calibration. Nevertheless, it will require a detailed knowledge of the pavement conditions, of the vehicle dynamics and of the sensor behaviour. As for a proper self-calibration procedure, the coefficients given in Equations (1) to (3) will have to be calibrated site by site and system by system, using a sufficient amount of known (statically weighed) trucks.

For pavement engineering and fatigue calculations, it would also be necessary to determine if the biases by axle rank are linked whether to the vehicle dynamics or to the sensors response. In the first case, these biases should not be removed, while in the second case it should be.

6. DISCUSSION

Each WIM-system has their own calibration system, which is a “black box” and outsiders cannot know how they work. General outlines of the calibration of those WIM-systems that participated in the CET at Lulea are described in chapter 3 “Calibration systems used at CET”.

Two test vehicles, a three-axle vehicle and a six-axle semi-trailer with tridems in the trailer were used during the calibration. They run totally 35 passes with full load and at four or three speeds, which was enough according to the participants.

An instrumented vehicle measures the instantaneous wheel load as the vehicle runs over a WIM-system. Thus dynamic loadings can be eliminated as the real wheel load is known when the vehicle passes over a WIM-sensor and real loads can be used in calibration. For this reason an instrumented vehicle seems to be an ideal tool for calibration of WIM-systems. Thus it was decided to use the instrumented vehicle of VTT for WIM-calibration at CET near Lulea and at CMT near Metz (multiple sensor WIM).

There are, however, certain difficulties. Dynamic wheel load changes even within the time as the wheel is on a bending plate. Strip sensors are more difficult because they are narrow in the direction of vehicle movement and the wheel load is determined by integrating stress values as the wheel runs over the sensor. Dynamic loading changes during this time but the algorithm for integration is in “a black box” and the procedure is not known for outsiders.

The real accuracy of the wheel load measurements in the instrumented vehicle is difficult to estimate because of the complicated measurement system. The measurement in the vehicle must be exactly matched to the positions of the WIM-sensors. In the instrumented vehicle used at WAVE the force is measured every 22 mm as the speed is 80 km/h and correspondingly more accurately if the speed is lower. The position is matched by reflective tapes, which are set usually at the intervals of 10.00 metres. Thus the maximum error in the position is 22 mm plus the error in the interval measurements of the tapes. The measurement interval comes from the sampling rate used at the measurement system and it can be selected to be greater if necessary.

Because the exact instantaneous value is not good for this purpose the mean value within 150 mm was selected and used later in this project.

Because of technical reasons the results of only one WIM-system could be compared to the results of the instrumented vehicle at CET. Relations between the axle loads measured by the bending plate WIM and by the instrumented vehicle or load coefficients (Figure 14 and Table 2) were the same for the first axle and second axle (1.106 and 1.111). They were slightly smaller for the third axle (1.065), which may be due to the short recovery time of the sensor for tandem axle. That may be more important in this case because the distance between the tandem axles is only 1.20 m and thus the WIM-sensors may give smaller axle load values for the latter axle. Because of technical reasons the accuracy of the third axle may be less than that of other axles. However, the behaviour of tandem axles may also explain the difference because also in some other measurements at CET the second axle within the tandem axle was underestimated by other WIM-systems, too (four WIM-systems all with different sensor types were used at CET) (Hallstrom & al 1999).

Bending plate WIM measurements give about 9% greater values than the instrumented vehicle based on the load coefficients (Table 2) and 7% greater if taken from the regression coefficients (Figure 14). The reason is likely that the instrumented vehicle measures the real dynamic wheel load, which is smaller on the plate than before or after (Figure 10, Figure 11, Figure 12 and Figure 13). The WIM-system is calibrated in order to compensate that difference. It is not known how the WIM-system takes the value (“black box”), perhaps the greatest bending? The instrumented vehicle used the mean value within 150 mm.

The corresponding sensor coefficients are defined at CMT (Metz) for each bar as the value measured by the instrumented vehicle is divided by the value measured by the WIM-sensor. These values are inverses to the load coefficients used at CET (Lulea). The sensor coefficients are presented in Figure 20 and in Appendix 1. The mean value from 18 sensors is for the first axle 1.15, the second axle 0.94 and the third axle 1.13. Thus results of the first and third axles are similar but that of the second axle is much smaller. The first and third axles are underestimated and the second overestimated. The overall sensor coefficient is 1.07, which means that loads are underestimated by 7%.

It is logical to use load coefficients as the axle load from the instrumented vehicle is taken as a “true” value, which is compared to the measured values by WIM-systems. As the instrumented vehicle is used for calibration, the inverse or the sensor coefficient is more practical because it is the value with which the value from a sensor must be multiplied in order to get the correct value. In order to make the comparison easier the load coefficients are converted to sensor coefficients, which are presented in Table 11.

Table 11 Sensor coefficients

	1st axle	2nd axle	3rd axle
CET (Lulea)	0.90	0.90	0.94
CMT (Metz)	1.15	0.94	1.13

The bending plate WIM-system does not see the difference between tyre types and thus the results are logical as the results from the first and second axles are similar and there may be good reason for the slightly greater value from the third axle. The situation for a strip sensor is different because the stress values from the sensors are integrated both in longitudinal and transverse direction. Because each WIM-system has its own secret black box it is not known if the width of the tyre imprint has any effect to the results. The easiest explanation is that the difference between the first and the second axle is due to the difference in tyres (single and dual tyres) but it does not explain the difference between the second and third axle. The behaviour of tandem axles can explain a part (but not all) of the difference within the tandem axles because at in some measurements at CET the second axle was underestimated by the WIM-systems (Hallstrom & al 1999). Four WIM-systems all with different sensor types were used at CET.

The instrumented vehicle was calibrated in Sweden immediately before the CET measurements and in France immediately before the CMT measurements.

The instrumented vehicle measures the instantaneous wheel load. WIM-systems are calibrated with passing test vehicles in order to get the static load of those vehicles. The WIM-system measures the instantaneous wheel load, which is not as great as the static load but may be smaller or greater because of dynamic effects (see 2.1). That instantaneous load is then multiplied by a calibration factor (or some more complicated method is used) in order to get the static wheel loads of the test vehicles. Thus it is clear that the wheel loads measured by the instrumented vehicle are not necessarily the same as the result from a WIM-system.

If only one axle of the instrumented vehicle is used in the calibration of the WIM-system this is not a problem because in that case the instantaneous load is exactly the same as used in the calibration of the WIM-system. That is a good research approach but not possible for real calibration because several types of loadings are necessary for effective and reliable calibration.

The standard deviations of the coefficients at CET (Lulea) are presented in Table 2 and at CMT (Metz) in Figure 21 and Appendix 1. In order to make them comparable the standard deviations at CET (bending plate) were calculated once again or as the standard deviations of sensor coefficients which are 0.0416, 0.0215 and 0.0789 correspondingly for the first, second and third axle. At CMT (strip sensors) the mean of standard deviations of all sensors are 0.127, 0.123 and 0.173 correspondingly for each axle. Thus the standard deviations are correspondingly 3.1, 5.7 and 2.2 times greater for the strip sensors than for the bending plate. That difference may be mainly due to the general accuracy and quality of the sensors but some effect may come from the algorithm, which was used in measurements, was not perhaps the best possible (simply mean value within 150 mm).

This instrumented vehicle used at WAVE is not ideal for this purpose because it is old and has relatively narrow tyres, which were used commonly at that time. Steel suspensions are neither ideal for an instrumented vehicle. VTT has later instrumented all axles of a new and modern vehicle (truck and semitrailer) and has now more experience in instrumented vehicles. The instrumentation itself is not expensive but selecting the best position for sensors requires experience and a shaker table is needed for calibration. The cost of a good vehicle is usually much more important (rental or buying).

The standard deviations at CET are 4%, 2% or 8% (the coefficients are close to 1) for corresponding axles, which include scatter from the instrumented vehicle and from the WIM-system. These measurements include also empty vehicles. Their standard deviations are greater because suspensions of heavy vehicles are designed for full loads (Hallstrom & al 1999). Tandem axles do not work as well as single axles; especially the second tandem axle is problematic. Thus real standard deviation for a good instrumented vehicle may be even less than half of those calculated here or of order 1-2%.

The use of axle rank in refining calibration provides promising results at CMT (Metz), where six WIM-systems were used and at an earlier test at Saint-Flour, where three WIM-systems were used. Systematic differences were found for many WIM systems, for some axles of the trucks weighed in motion. These differences depend on the axle ranks, and may be partially explained by phenomena due to the pavement conditions, to the dynamics of the vehicles and to the sensor behaviour.

A calibration by axle rank can remove or reduce these differences and thus improve the WIM accuracy for static weights and loads estimation. These preliminary results still have to be verified on a larger scale, with more test data. It is expected that in some circumstances, one accuracy class may be gained using this procedure. The procedure is easy to implement, either in a self-calibration algorithm or as a specific algorithm for the WIM-systems, which do not use any self-calibration. Nevertheless, it will require a detailed knowledge of the pavement conditions, of the vehicle dynamics and of the sensor behaviour. As for a proper self-calibration procedure, the coefficients will have to be calibrated site by site and system by system, using a sufficient amount of known (statically weighed) trucks.

Based on these measurements it is impossible to know to which degree the differences by axle rank are linked to the vehicle dynamics or to the sensor response.

Four WIM-systems participated in the CET test at Lulea. They all use different principles and sensors, a bending plate, a quartz module sensor, a piezoceramic nude cable (self-calibration) and a bending plate below the asphalt surfacing (Hallstrom & al 1999). In most cases there was no or very small effect of the axle rank and usually only in the case if the vehicle is empty (besides the report other unpublished figures were checked). If there was any difference, the first axle and the second axle of the tandem axle were underestimated

As the instrumented vehicle was used at CET there was no difference between first and second axle but there was a very clear difference at CMT (Table 11).

Thus it is likely that the axle rank itself has only very little effect and it is not necessarily an important phenomenon. It may have something to do with the self-calibrating system (all at CMT are self-calibrating WIM-systems) or with the strip sensors, which may be sensitive for the tyre imprint, perhaps more specifically for the tyre width. Also tyre inflation pressure may have something to do with it. Noteworthy, too that the magnitudes in rank effects at CMT are different at from a system to another.

As shown in Chapter 5 the calibration by axle rank is a promising method in order to increase the accuracy of self-calibrating WIM-systems. Further research is recommended.

For pavement engineering and fatigue calculations, it would also be necessary to determine if the inaccuracies by axle rank are linked whether to the vehicle dynamics or to the sensors response. In the first case, these inaccuracies should not be removed, while in the second case it should be.

7. CONCLUSIONS AND RECOMMENDATIONS

Even if the WIM-systems themselves were perfect calibration is needed because of site dynamics and local traffic conditions. Each new WIM installation will have different characteristics, which will cause vehicles to behave in different ways. In order to minimize the effects of these factors on the accuracy of the WIM measurements each new site requires calibration.

In addition to local differences in site dynamics the types of traffic will affect the measurements. In particular the normal types of suspension and loading will, combined with the site dynamics, require unique calibration figures for the local conditions.

This report is based mainly on the results and experiences gained at the Cold Environment Test (CET) at Lulea, on measurements with the instrumented vehicle at CET and at Continental Motorway Test (CMT) at Metz and on the research concerning the effect of the axle rank at Metz. The work at the WAVE project is organised so that CET is handled in the Work Package 3.1 and the calibration issues in the Work Package 3.2. This report is the final report of WP 3.2. The Cold Environment Test (WP 3.1) is presented in another report (Hallstrom & al 1999). It is difficult to define exactly which facts should be presented in WP 3.1 report and which in this WP 3.2 report. Thus it is highly recommended to read also WP 3.1 report (Hallstrom & al 1999).

The Lulea test (Hallstrom et al 1999) has shown very clearly that a simple use of statistical tests may be misleading. It was found that in reality all regression lines go through the origin (in practice very close) and no bias at all or very small bias existed. In practise only certain self-calibrating systems may have bias. If bias is found it is very likely that there is a specific reason for it and those points may be for instance outliers and should be taken away. Than can be only found if scattergrams are made where every result can be seen as a point.

The test site at Lulea was very even but also there the dynamic effects of vehicles were important. Most heavy vehicles run at the maximum legal speed. The use of different speeds in calibration is highly recommended because the different dynamic properties of the vehicle fleet passing over the WIM-systems can be simulated with several speeds. Because of that at least two speeds of the test vehicles are necessary but three is recommended.

The sensitivity for speed can be seen with several speeds even that is not usually important because the speed at the WIM-stations is rather constant. The sensitivity for speed may, however, reveal other problems.

The vehicles were driven full-loaded, half-loaded and empty. Because axles, especially the tandem axles of empty vehicles may be “jumping” the usefulness of empty vehicles in calibration is doubtful. The reason is simple; the suspensions are designed to work well at full load and are not so good if the vehicle is empty. It is important, too that the accuracy of the WIM-systems is good at full load or overload and less important as the wheel load is smaller.

If self-calibrating systems are used it is very important that the traffic runs really on the sensors also before the test because it may take even several days before enough data is collected.

Because the temperature range was wider at Lulea than in for instance in Central Europe and some WIM-sensors was found to be temperature sensitive in cold climate (Hallstrom & al. 1999). It is highly recommendable to the manufacturers to make some tests also at extreme temperatures.

The preceding findings should be taken into account at the WIM Specifications (COST323 1997).

Every manufacturer has its own procedure for calibrating their WIM-systems. Because the measurement systems are not public and the organisers of the test could not follow the calibration procedure there are no possibilities to give more exact recommendations. Hopefully the manufacturers could learn themselves from these tests and the reports published (Hallstrom & al 1999 and this report).

The instrumented vehicle of the Technical Research Centre of Finland (VTT) was used at CET (four WIM-systems) and at CMT (multiple sensor WIM-system). It measures the instantaneous wheel load of all axles (the front axle and the tandem axle).

At Lulea (CET) there was a systematic difference (7-9%) between the measurement results of the bending plate WIM-system and the instrumented vehicle or the sensor coefficients were 0.90, 0.90 and 0.94 correspondingly for the first, second and third axle. The bending plate causes very specific changes in the instantaneous dynamic axle loads. The definition of the instantaneous dynamic axle load on the bending plate is not unique. The difference is compensated by calibration and thus systematic difference is natural.

The scatter was reasonable small (standard deviations 4%, 2% and 8% correspondingly for each axle). There are no means to know how much of it is due to inaccuracy of the instrumented vehicle and how much due to the WIM-system.

The instrumented vehicle calibrated multiple WIM sensors at Metz (CET). The results were not very good and the mean of the sensor coefficients are 1.15, 0.94 and 1.13 correspondingly for each axle. Standard deviations are 2 to 6 times greater than at CET. That difference may be mainly due to the general accuracy and quality of the sensors but some effect may come from the algorithm, which was used in measurements. As the wheel load varies even within a short distance it is difficult to define, which load should be used as the strip sensor is narrow in the direction of the vehicle movement. The load was taken as the mean value within 150 mm. The accuracy of the vehicle positioning system is 22 mm plus the accuracy of the tapes but because the reflective tapes were not installed with the same accuracy as in CET the accuracy may be some worse.

It is likely that the strip sensors used at the multiple sensor WIM may be sensitive to tyre types (single, dual), tyre width, size of tyre imprint and/or tyre inflation pressures.

The instrumented vehicle measures the instantaneous wheel load. WIM-systems are calibrated with passing test vehicles in order to get the static load of those vehicles. Thus the WIM-system measures the instantaneous wheel load which is then multiplied by a calibration factor (or some more complicated method is used) in order to get the static wheel loads of the test vehicles. Thus it is natural that the wheel loads measured by the instrumented vehicle are not necessarily the same as the result from a WIM-system. If the “black box” of the WIM-system were known the difference might be solved.

The preceding phenomenon may limit the use of an instrumented vehicle for calibration or at least more research is needed. However, an instrumented vehicle is an excellent tool as the behaviour and the performance of sensors and WIM-systems are studied and analysed.

The instrumented vehicle can be used to study for instance the effect of WIM sensors to the dynamic loading. It can be used also to study spatial repeatability of dynamic loadings. Because probably only one vehicle is available, the effect of variability of vehicles can be compensated with changing speeds (see Huhtala & al 1992, 1993, 1994).

The instrumented vehicle of VTT has been instrumented for other purposes and not specially for calibrating WIM-systems. It is more than 25 years old and has the tyre sizes from that time. Tyres are narrower and smaller than those widely used at the present time. VTT has later instrumented another vehicle (a truck with semi-trailer), which is new, very well maintained and it has air suspensions on all axles. It was used in another international research project. The instrumentation of a vehicle demands experience and a shaker table is necessary for calibration. The cost of instrumentation and calibration of a vehicle is not much compared to the vehicle cost (buying or rental).

The standard deviation of the dynamic load measurements will likely be about 1-2% if a new and good vehicle is used and the instrumentation and the calibration are made properly. That standard deviation includes the scatter both in dynamic force measurement in the vehicle and at the good quality WIM-system. The systematic error may be a problem as presented earlier.

The use of instrumented vehicle for research is strongly recommended based on the experience gained in this research project. It is also a promising tool for calibration but further research is needed and thus no exact recommendations can be given how it should be used for calibration.

The use of axle rank in refining calibration of self-calibrating WIM-systems provides promising results at CMT (Metz), where six WIM-systems were used and at an earlier test at Saint-Flour, where three WIM-systems were used. Systematic biases were found for many WIM systems, for some axles of the trucks weighed in motion. These biases depend on the axle ranks, and may be partially explained by phenomena due to the pavement conditions, to the dynamics of the vehicles and to the sensor behaviour.

A calibration by axle rank can remove or reduce these differences and thus improve the WIM accuracy for static weights and loads estimation. These preliminary results still have to be verified on a larger scale, with more test data. It is expected that in some circumstances, one accuracy class may be gained using this procedure. The procedure is easy to implement, either in a self-calibration algorithm or as a specific algorithm for the WIM-systems, which do not use any self-calibration. Nevertheless, it will require a detailed knowledge of the pavement conditions, of the vehicle dynamics and of the sensor behaviour. As for a proper self-calibration procedure, the coefficients will have to be calibrated site by site and system by system, using a sufficient amount of known (statically weighed) trucks.

Based on these measurements it is impossible to know to which degree the differences by axle rank are linked to the vehicle dynamics or to the sensor response.

For pavement engineering and fatigue calculations, it would also be necessary to determine if the inaccuracies by axle rank are linked whether to the vehicle dynamics or to the sensors response. In the first case, these inaccuracies should not be removed, while in the second case it should be.

The calibration by axle rank is promising method in order to increase the accuracy of self-calibrating WIM-systems. Further research is needed and recommended.

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APPENDIX 1.

MEAN VALUES					
SENSOR	GW	AXLE 1	AXLE 2	AXLE 3	TANDEM
-1	1,04	1,13	0,95	1,10	1,00
0	1,06	1,17	1,00	1,05	1,01
1	1,04	1,20	0,92	1,08	0,99
2	1,16	1,46	1,00	1,20	1,08
3	1,16	1,26	1,03	1,29	1,12
4	1,07	1,25	0,95	1,07	1,00
5	1,05	1,19	0,91	1,15	1,00
6	0,95	0,98	0,89	1,02	0,94
7	0,71	0,74	0,72	0,70	0,71
8	1,08	1,13	0,95	1,23	1,06
9	1,09	1,16	0,99	1,17	1,06
10	1,07	1,25	0,97	1,07	1,01
11	1,03	1,15	0,87	1,18	0,99
12	1,13	1,17	1,00	1,30	1,11
15	0,94	1,14	0,80	1,00	0,88
16	1,14	1,09	1,01	1,49	1,17
Mean	1,04	1,15	0,94	1,13	1,01

STDEV					
SENSOR	GW	AXLE 1	AXLE 2	AXLE 3	TANDEM
-1	0,066	0,106	0,084	0,109	0,061
0	0,083	0,080	0,096	0,224	0,106
1	0,112	0,087	0,136	0,200	0,135
2	0,128	0,328	0,134	0,152	0,109
3	0,085	0,110	0,130	0,138	0,091
4	0,073	0,075	0,075	0,147	0,088
5	0,067	0,071	0,080	0,151	0,085
6	0,111	0,137	0,111	0,182	0,109
7	0,133	0,231	0,148	0,099	0,114
8	0,075	0,082	0,097	0,145	0,093
9	0,092	0,095	0,125	0,142	0,109
10	0,116	0,168	0,151	0,141	0,113
11	0,118	0,132	0,116	0,165	0,122
12	0,110	0,106	0,128	0,199	0,123
15	0,181	0,153	0,186	0,280	0,216
16	0,120	0,066	0,171	0,290	0,182
Mean	0,104	0,127	0,123	0,173	0,116

Figures

Tables