INSTRUMENTED VEHICLE AND ITS USE FOR CALIBRATION OF WIM-SYSTEMS

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ABSTRACT

As a vehicle drives on a road the instantenous wheel load is not steady, eg 10 tons but is varies because of the unevenness of the road. This varying axle load is often called as dynamic axle load. All weigh-in-motion (WIM) systems must be calibrated at site. The instrumented vehicle measures instantenous wheel loads and thus seem to be an exellent tool for calibration of WIM-systems. The instrumented vehicle of VTT was used in calibration measurements at WAVE tests near Lulea in Northern Sweden and near Metz in France. The use of instrumented vehicle was more complicated than assumed. It is not only question of the accuracy of the measurement system nor the accuracy of matching the measurements at the vehicle and at WIM-systems but also a problem: what is really expected from the calibration. The (good) results and problems are presented in this paper.

1. INTRODUCTION

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 1):

- 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.

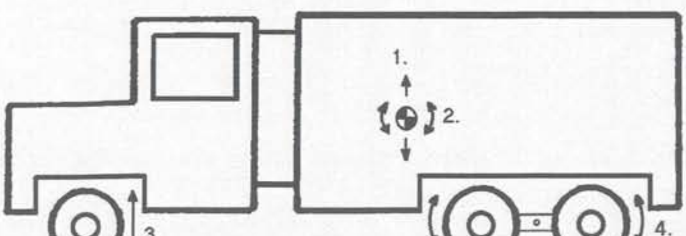

Figure 1 Dynamic movements of vehicle; body bounce (1), body pitch (2) and axle hop (3) and tandem pitch (4)

Weigh-in-motion (WIM) systems measure the instantenous dynamic axle loads of the passing vehicle. The main interest is, however, to know the static axle loads of the passing vehicles and based on these the gross weight of the vehicle. WIM-systems are installed on even, straight road sections in order to minimize dynamic loadings and therefore there is very little rolling and other movements. In certain cases harsh weather conditions, for instance wind or ice on pavement may excite other dynamic movements.

There are several sources of errors in WIM-systems and therefore the calibration of each WIM-system is very necessary (see for instance Huhtala & al 2000). That is usually done using test vehicles and/or vehicles from the traffic flow which are measured statically after passing the WIM-system. As the instantenous dynamic axle load can be measured by an instrumented vehicle it is very temptating to use it in the calibration of WIM-systems.

2. DYNAMIC AXLE LOAD MEASUREMENT SYSTEM

Three main principles of measuring dynamic axle loads are:

- the change of the distance between the axle and the road surface is measured (flattening of the tyre),
- instrumented rim,
- bending of axles or shear strains in the axle are measured with strain gauges.

The first one is no more used. An instrumented rim is good but expensive, which means that dynamic loadings can be measured simultaneneously only at one wheel. Because of its slightly greater weight and dimensions it may also change the dynamic properties of the suspension and moves tyres outwards. The measurement of bending of the axles or shear strains in the axle is cheap with strain gauges and all axles can be measured simultaneously. The authors have instrumented with strain gauges an own and a rented vehicle and have used two other in an earlier research project. Thus this paper is limited only to dynamic loading measurements with strain gauges.

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 or shear strain on the sides of the axle. An inertial force component is measured with an accelerometer. Figure 2 shows the arrangement as bending is measured. If shear strains are measured the strain gauges are at the sides of the axle (not shown in Figure 2).

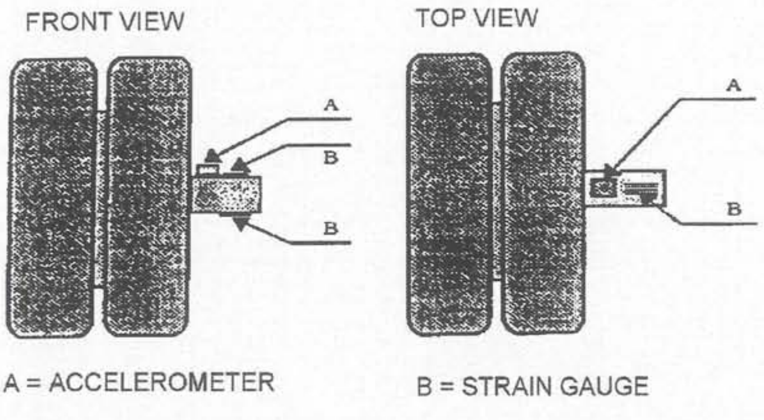

Figure 2. The locations of the sensors on the axle of vehicle

The location of strain gauges is critical especially in complicated suspension systems. Particually the location of shear gauges demand special attention, experience and judgement.

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 of VTT consists of amplifiers for the strain gauges and an 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 the second time). Typical sampling rate used is 1000 Hz. Cut-off frequency for the digital filter is 50 Hz.

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 should 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. As the vehicle after WAVE was calibrated also real road profiles were used in calibration.

Thus the calibration of the dynamic loading system is based on the equation presented earlier:
Fs = (static wheel load) is measured by static axle weighing pad before or after each measurement series (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.

Dynamic calibration is not only important for the calibration of the system but it may reveal problems in the incorrect location of strain gauges or hysteresis in suspension components which may cause considerable errors in measurements.

VTT has instrumented 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 & al 1999). In principle the system is the same but shear strain gauges were used. They are less sensitive for transverse lateral forces but their place must be more carefully selected. Because WIM-stations are on straight parts of roads this is not very important. The principle of measurement and calibration is the same as described earler.

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. 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.

3. CALIBRATION OF WIM SYSTEMS WITH AN INSTRUMENTED VEHICLE

3.1 General

WAVE (weigh-in-motion of axles and vehicles in Europe) is a fourth Framework Programme of the European Commision. Work package 3.2 in handled the calibration of WIM-systems (Huhtala & al 2000). It included tests near Lulea in Northern Sweden and near Metz in France. The instrumented vehicle of VTT was used at both test sites and most results in this paper are based on those two tests.

The instrumented vehicle used at the Lulea and Metz test is owned and instrumented by VTT. It is old but a common three axle rigid lorry in Finland, SISU. 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.

Instrumented vehicle has been used earlier in UK and France at 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.

3.2 Measurements at Lulea

The measurements were made at Lulea on 9 - 10 June 1997. Five WIM-systems participated in the test but only one could be used for calibration with the instrumented vehicle. One selfcalibrating system had not yet enough material for reliable measurements, one used two sensors and data could not be attained separately from them and one was not yet ready for measurements. The test lasted longer than one year but because of economical reasons the instrumented vehicle could not be used later on the test site. The instrumented vehicle was used on a good quality bending plate WIM system. An example of the results is presented in Figure 3.

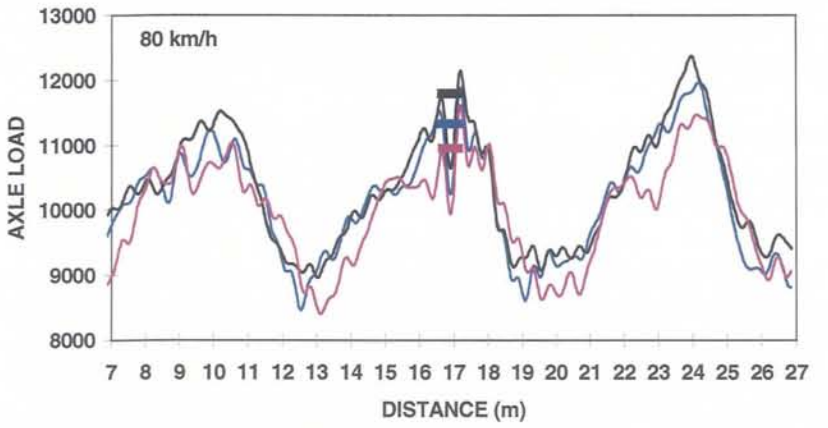

Figure 3. Dynamic axle loads of the driving axle over one WIM-system, three vehicle passes.

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 4 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.

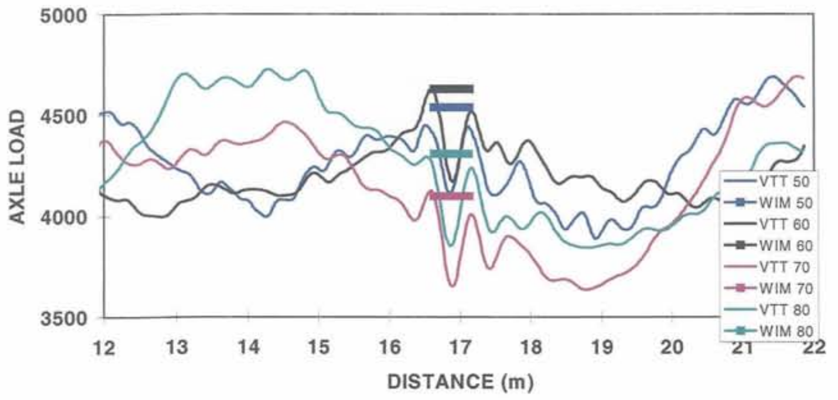

Figure 4. Dynamic axle loads of steering axle and corresponding WIM-measurements

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 4.

The same phenomenon is found in Figure 5 (driving tandem axle) and in carrying bogie axle (no Figure here).

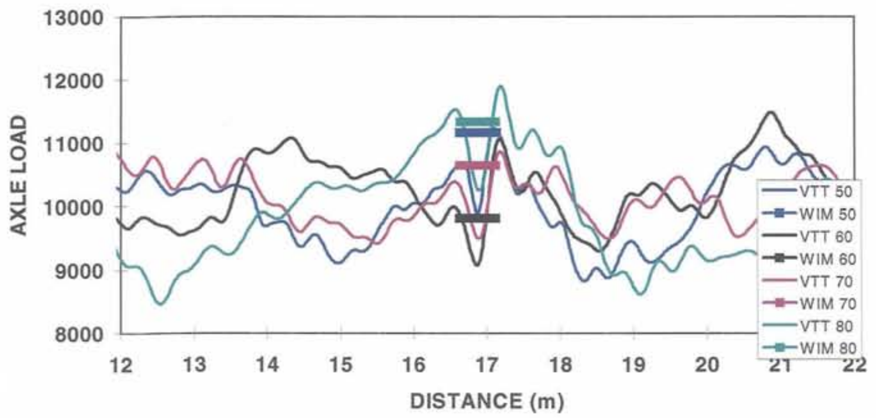

Figure 5. Dynamic axle loads of driving axle and corresponding WIM-measurements

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 6. 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.

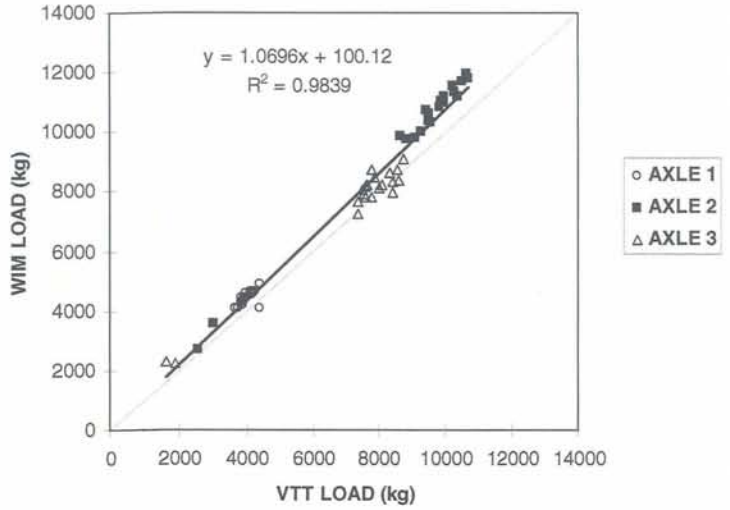

Figure 6. Dynamic axle loads measured in the vehicle (VTT) and by a WIM-system

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 (second tandem axle) are more scattered and the measured axle loads are smaller. 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. That axle can be lifted if the vehicle is empty or near empty. The more complicated mechanical system makes its dynamic properties worse than that of the first tandem 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) 1.106, 1.111, 1.065 correspondingly and 1.094 for all.

The scatter in Figure 6 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 3 - 6 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.

3.3 Measurements at Metz

Multiple sensor WIM was used at Metz or all 18 strip sensors were identifical. 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 7.

It can be seen from Figure 7 that the coefficients of the first axle 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).

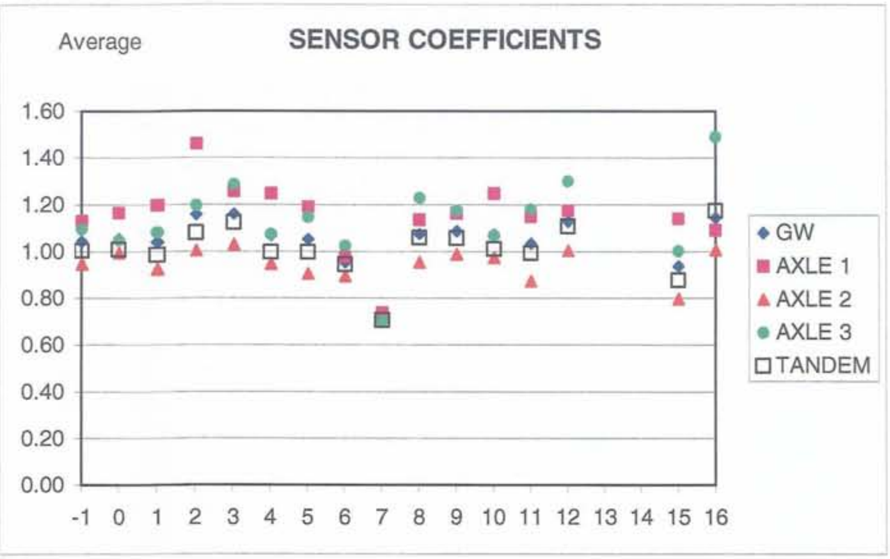

Figure 7. Sensor coefficients axle by axle, mean value of all passes but as the bump was used.

The mean value of the axles in tandem is presented as squares in Figure 7. 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 7 is the mean value of all coefficients.

4. DISCUSSION

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.

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.

Because of technical reasons the results of only one WIM-system could be compared to the results of the instrumented vehicle at Lulea. Relations between the axle loads measured by the bending plate WIM and by the instrumented vehicle or load coefficients (Figure 6) 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. The second axle can be lifted if the vehicle is empty or near empty and as full load it carries about 45% of the load. The more complicated mechanical system makes its dynamic properties worse than that of the first tandem axle. 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 (Hallstrom & al 1999).

Bending plate WIM measurements give about 9% greater values than the instrumented vehicle based on the load coefficients and 7% greater if taken from the regression coefficients (Figure 6). The instrumented vehicle measures the real dynamic wheel load, which is much smaller in the middle of the plate than before or after because of the dynamic forces (Figure 3-5) and also much smaller than the static weight of the axle. The manufacturer does not necessarily know it and it is not important for him because the WIM-system is calibrated with test vehicles in order to compensate that difference.

The instrumented vehicle used the mean value within 150 mm and not the peak value. If the exact value in the middle of the plate had been used been used the difference would have had even been greater.

Even the bending plate was installed very well and was at the same level as the pavement surface, it excited dynamic forces and got them in the same phase (Figures 4 and 5) or in very good spatial repeatability. Even only one vehicle was used here different speeds (50, 60, 70 and 80 km/h) simulated the effect of different vehicles as the dynamic properties are time (frequency) related. This phenomenon probably increases the accuracy of a bending plate WIM-system. The idea of using small exact unevenness to excite spatial repeatability has been presented in an earlier paper (Huhtala & al 1992), which was based on computer simulations but never studied further.

The corresponding sensor coefficients are defined at 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 Lulea. The sensor coefficients are presented in Figure 7. 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%. Standard deviations are 2 to 6 times greater than at the bending plate at Lulea. That difference may be due to the general accuracy and quality of the sensors but some effect may come from the algorithm, which was used in measurements.

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, 0.90, 0.90 and 0.94 correspondingly for the first, second and third axle. These numbers mean that the WIM systems gave smaller load than the instrumented vehicle.

The dynamic force was the mean load within 150 mm. The length of the tyre imprint depends on the tyre size, load and tyre inflation pressure, 300 mm can be taken as a rough estimate. Thus instrumented vehicle measured only the center part of the imprint and thus gave greater load than the WIM-system. The algoritms in the instrumented vehicle and in the WIM-systems should be "coordinated" but that is impossible because those algoritms are in secret "black boxes".

If exactly same length will be used the accuracy of matching measurements to the WIM-station should be exact. The maximum error in these measurements was in principle 22 mm at the speed of 80 km/h plus the inaccuracy in the installation of the reflective tapes which caused some problems at Metz.

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 smaller 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 in some measurements at Lulea the second axle was underestimated by the WIM-systems (Hallstrom & al 1999). The results from Metz were analysed by the French WAVE colleaques and VTT provided only the results from the dynamic force measurements and thus the authors could not analyse the results further (all the available results are in refence: Huhtala et al. 2000).

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. 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 instrumented vehicle is first calibrated statically and then dynamically on shaker table. The dynamic calibration takes into account the pseudomass of the suspension but is not absolutely necessary because the road where WIM-system is used is relatively even and vertical accelerations are small. Dynamic calibrations on shaker table are, however, important as the quality control of the measurent system. They may reveal for instance hysteresis in the systems which cannot be tolerated. The steel suspension of the instrumented vehicle used at WAVE had no hysteresis. The suspensions of vehicles to be instrumented should be simple. If the suspension is complicated it may be difficult to find a good, suitable place for strain gauges. VTT instrumented a new tractor-semitrailer vehicle with air suspensions. The tractor presented no problem but an important hysteresis was found in the trailer suspension and it was not used for measurements. The reason may be the complicated structure with many joints and possibly rubber or plastic parts. Unfortunately it was not possible for us to analyse the problem further.

This instrumented vehicle used at WAVE is good but not ideal for this purpose because it is old and has relatively narrow tyres, which were used commonly at that time. 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 knowledge, experience and judgement. The cost of a good vehicle is usually much more important (rental or buying).

5. 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.

An isntrumented vehicle measures continously the dynamic wheel load and thus might be ideal for calibration of Weigh-in-Motion systems. The main conclusions from the research made by VTT can be presented as follows:

1. Dynamic Axle Loads in all axles of a vehicle can be measured with strain gauges and accelerometers with good accuracy, relatively easily and at low cost; the cost of the vehicle is more crucial. Selecting proper position of strain gauges and accelerometers needs knowledge, experience and good judgement.
2. The instrumented vehicle must be calibrated statically and on shaker table dynamically. As the vertical accelerations on an even road are not important dynamic calibration is not essential but it may reveal hysteresis and other problems. Dynamic calibration is especially important if complicated air suspensions are used.
3. The exact match of dynamic wheel loads to WIM-stations is important and careful measurements of the locations is vital.
4. The aim of WIM-systems is to get static wheel or axle loads and based on them the gross weight can be calculated. In reality the WIM-system measures the dynamic wheel load on the sensor but it is calibrated with test vehicles to get the static load which may be considerably different from the dynamic load measured by the WIM-system. The instrumented vehicle measures basically the same dynamic load

which may be also different from the static load. Thus the value of dynamic loads measured by intstrumented vehicle may be doubtful as a calibrating instrument but, however, useful as a research tool.

5. The instrumented vehicle measures the instantenous wheel load. WIM-stations measure the passing axle or wheel loads. If a bending plate is used the maximum axle wheel load of the passing wheel is probably measured by the WIM-system and it can be compared to the maximum wheel load on the bending plate measured by the instrumented vehicle. If a strip sensor is used the tyre/sensor contact stress is measured and integrated. The exact dynamic load during the vehicle pass over the narrow sensor is probably not the correct way but which is the best way to coordinate the algoritms of black boxes which should be "opened". Further research is needed.
6. It must be noted that the wheel load on the bending plate or during the pass over the strip sensor is not constant but changes all the time because of dynamic loading. There is not an unequivocal instant wheel load for a WIM-sensor.
7. Spatial repeatability changed over the bending plate because of the small roughness caused by the bending plate. That probably made the results better but further research is needed (the same has been seen in earlier computer simulations made by the authors).
8. If an instrumented vehicle is used for calibration it should also be used as the main test vehicle in the calibration of WIM-systems in order to get all benefit from the measurements of dynamic loadings.
9. The use of instrumented vehicle for research is strongly recommended. 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.
10. 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.

REFERENCES

Hallstrom,B., Caprez, M., Halonen, P., Huhtala, M., Jehaes, S., Juurinen, M-T. & O'Brien,E. (1999), WP 3.1 Durability of WIM sensors in cold climate. WAVE report. Swedish National Road Administration. 1999.

Huhtala, M., Pihlajamäki, J. & Halonen, P. (1992), WIM and dynamic loading of pavements. Heavy vehicles and roads. Proceedings of the third international symposium on heavy vehicle weights and dimensions. Cambridge, UK June 28 - July 2, 1992. pp. 272 - 277.

Huhtala, M., Halonen, P. & Pihlajamäki, J. (1993), Spatial Distribution of Dynamic Loadings on Pavements. Preprint 931062. TRB Annual Meeting 1993. Washington D.C. 20 p.

Huhtala, M., Vesimäki, M. & Halonen, P. (1994), Computer Simulation of Road-Vehicle Dynamic Interaction Forces of Three and Four-Axle Trucks. Vehicle - Road Interaction II Conference held in Santa Barbara, California May 17-22 1992. Vehicle-Road Interaction, ASTM STP 1225, B.T.Kulakowski, Ed. American Society for Testing and Materials, Philadelphia, 1994, 1994, pp. 36-51.

Huhtala, M., & Jacob, B. (1995), OECD/DIVINE project – Spatial repeatability of impact forces on a pavement, Post-proceedings of the 1st European conference on WIM, ed. B. Jacob, Zurich, March 8-10, 1995.

Huhtala, M, Halonen,P & Sikiö,J (1999), Measurements on dynamic effects of dual and wide base single tyres. COST-334 report. VTT-YKI 1999. 45 p

Huhtala, M. & Halonen, P. Calibration of WIM-systems. Weigh-in-motion of road vehicles for Europe (WAVE). Report of Work Package 3.2. Technical Research Centre of Finland, 2000. 63 p.

Jacob, B. & Dolcemascolo, V. (1995), Spatial Repeatability of Axle and Vehicle Impact Forces on a Pavement, OECD/DIVINE project, Element 5, Final report, LCPC/OECD, 1995. Paris.