2

WEIGH IN MOTION

2.1 INTRODUCTION

Transport plays a major role in the social welfare and economic growth of a community. Governments are responsible for this network and they must ensure that people can carry out their activities in safe and effective conditions. Most of this transport is provided by road infrastructure, which are severely damaged by heavy goods vehicles. If knowledge of the traffic composition was improved, the design, construction and maintenance costs of roads and bridges could be decreased. In addition, the reduction of trading barriers between European countries and the demand for ensuring fair competition have emphasised the need for more strict vehicle weight control. Traditionally, this task had been carried out by static weighing scales. However, this system only gets information on a reduced number of vehicles and the search for new more effective procedures has become a priority in the policy of many road authorities, particularly in Europe.

Weigh-in-Motion (WIM) is the technology that appeared to overcome the limitations of static weighing scales. A first division of WIM systems can be made by distinguishing On-Board WIM from Pavement or Bridge based WIM. The first group computes gross vehicle weight solely from measurements of force and acceleration taken through equipment in the vehicle. The second group consists of measuring wheel effects in sensors mounted in or on the road pavement or on an existing bridge structure, and estimating the corresponding static loads with appropriate algorithms. Depending on the speed of operation, pavement WIM systems can be classified in two basic categories: low-speed WIM (LS-WIM) and high-speed WIM (HS-WIM). A LS-WIM system is installed in a specific weighing area where vehicles are diverted from traffic flow and weighed at speeds lower than 15 km/h. These systems are accurate enough for legal enforcement and road pricing. A HS-WIM system is installed in the traffic lanes and continuously collects data on truck weights, speeds, time of travel, axle configurations and traffic patterns as they pass at normal speeds. The main advantage of HS-WIM systems is that all trucks are recorded with minimal or no interruption to the traffic flow. The information provided by these systems is used in statistical calculations relating to pavement, bridge and road management applications.

2.2 THE DEVELOPMENT OF WEIGH IN MOTION TECHNOLOGY

Research on WIM systems for the estimation of vehicle weights as they travel at full speed has been going on since the 1950's in the United States. Early studies measured the mechanical strain induced in load cells and highway bridges to derive the corresponding weights. In the 1960's and 1970's, the digital computer made it possible to handle the large quantity of data supplied by these sensors. In the 1970's and 1980's sensors embedded in or placed on the road became commercially available. In the mid-1990's, On-Board WIM started to be an object of study under contract with the American Federal Highway Administration (FHWA)[1]. A large quantity of WIM data has been collected within the Long-Term Pavement Performance (LTPP) program in the US[2].

France and the UK initiated the development of WIM in Europe in the 1970's. Some European countries expressed a great demand for WIM, and in 1992, the Forum of European Highway Research Laboratories (FEHRL) underlined WIM as a priority topic for co-operative actions to be supported by the DG VII of the European Commission. As result, COST323 (WIM-LOAD) (1993-1998), part of the COST (**C**o-**O**peration in **S**cience and **T**echnology) Transport programme, was initiated as the first European co-operative action on Weigh-In-Motion of road vehicles. Its objective was to promote the development and implementation of WIM techniques and systems throughout Europe. Another objective was to provide a significant step forward in the understanding of WIM performance and applications with respect to road network manager's and decision maker's requirements. It was also necessary to harmonise and explain the best practice of WIM for the users and vendors, as well as to fix the vocabulary to facilitate communication between them. The main objectives of the COST323 action were (Jacob 1998a):

- Inventory of WIM requirements in Europe.
- Collection and evaluation of existing WIM information.
- Preliminary work on the development of a European technical specification on WIM.

- Agreement of mechanisms and protocols for a pan-European database of WIM sites and data.
- Collection and dissemination of scientific and technical information.
- Exchange of experiences and conclusions from other international projects.
- Recommendations on the application of WIM to enforcement and traffic management, bridge and pavement engineering.

A reduced glossary of WIM terms and European Specification on WIM, a result of the COST 323 action, are given in Appendices A and B respectively.

Another large European research project, WAVE (**W**eigh in motion of **A**xles and **V**ehicles for **E**urope) supported by the European Commission, started in 1996 with a duration of two years. The project was organised in four main packages (Jacob 1999):

- Accurate estimation of static weights using WIM systems: Multiple Sensor WIM and Bridge WIM.
- Quality, management and exchange of WIM data: WIM data quality assurance, and WIM data format and database structures.
- Consistency of accuracy and durability: durability of WIM systems in cold climates and calibration of WIM systems.
- Optical WIM sensors, technology for the future: sensor design, optoelectronic head, and data acquisition and processing unit.

Nowadays, there are about 1000 WIM stations working around the world of which approximately 45% are in the US, 30% in Europe and 15% in Australia. Figure 2.1 shows the countries participating in the COST323 action and WAVE projects and the approximate number of WIM sites in Europe. More information about the COST323 action or the WAVE projects can be found in their web sites[3,4,5].

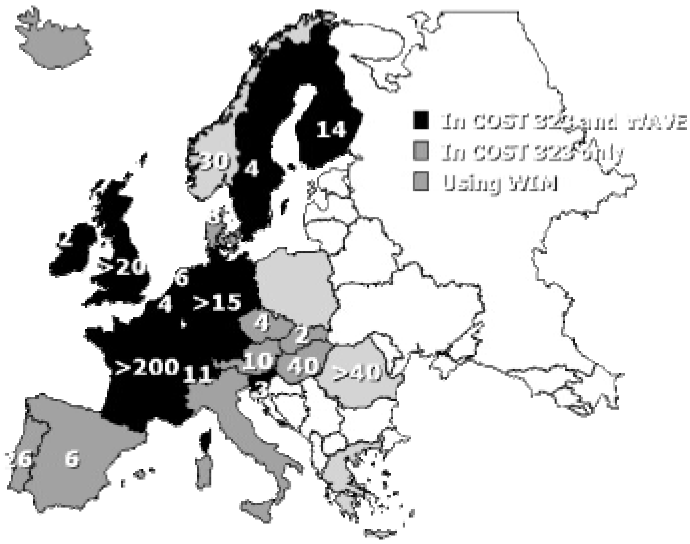


Figure 2.1 – Approximate number of WIM stations in Europe[6]

2.3 STATIC WEIGHING SCALES

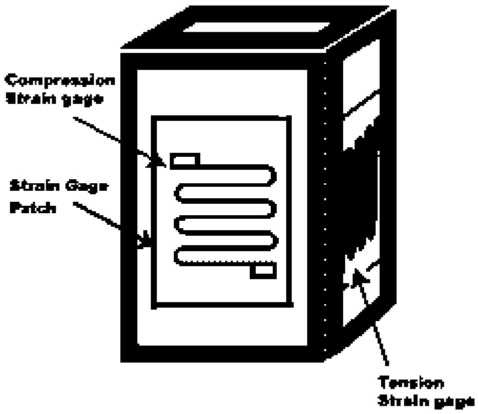
Until the appearance of WIM systems, static weighing was the only way to detect overweighing. The dissuasive effect caused by static scales was small as only a reduced number of vehicles could be intercepted, stopped and diverted to static weighing areas. Compared to a WIM system, a static scale can store and retrieve additional information on customers, products, hauliers, driver Ids, vehicle registrations, trailer Ids, stored tares for tractors and trailers, suppliers and destinations. Some of these features can be obtained with WIM systems if used in combination with video (Henny 1999).

A truck scale consists of a scale frame that supports the weight of a truck without major bending, load cells, junction boxes and a weight indicator. There are two types: Stationary platform scales and portable wheel load scales. The accuracy of both systems makes them eligible for enforcement purposes.

2.3.1 Platform Scales

As the truck rolls on to a scale, the load cells register the pressure from the wheels. Each load cell converts this pressure into an electrical signal through strain gauges placed on its surface with special adhesives. As the surface to which the gauges are attached becomes strained, they stretch or compress changing their resistance proportionally to the applied load (Figure 2.2(a)). The precise positioning of the gauges, the mounting procedure, and the materials used all have a measurable effect on overall performance of the load cell. The electronic signals from all of the load cells are sent out to junction boxes. Junction boxes sum all of the signals into one indicator that shows how much the truck weighs.

These traditional scales are available in a wide range of sizes and weighing capacities, in both pit-mounted and surface-mounted versions, with steel or concrete platforms (see Figure 2.2 (b)). A platform scale gives a typical maximum permissible error band of 0.5% for the gross vehicle weight. However, as vehicles must be stopped on the scale, the weighing system is time consuming and inconvenient for drivers. WIM systems overcome this problem, but their calibration and testing still depends on the information supplied by a reliable static weighing scale.



(a) Strain gauges (b) Static platform

Figure 2.2 – Static weighing

2.3.2 Portable wheel load scales

Portable wheel load scales have been developed to allow for measuring wheel and axle loads as well as gross vehicle weights. They are also used for spot checks. Each wheel is measured individually, but their precision is somewhat lower than platform scales. Depending on how many scales are used, additional errors may occur because of weight transfer between axles in vehicles with 3 or more axles. The sources of these errors are:

- Longitudinal tilting of the vehicle
- Wrong sensor levelling
- Site evenness

- Sensor tilting
- Mechanical friction in the suspension
- Residual friction forces induced by braking

The influence of these factors in the results in axle group or gross vehicle weight is reduced by using the same number of scales as number of wheels in an axle group or in the whole vehicle. A set of 6 wheel load scales can achieve a maximum error band of less than 1% in gross vehicle weight, but they are slow and require a lot of labour. A set of 2 wheel load scales can achieve a maximum error band between 1% (good site and vehicles in good condition) and 3% (average site and vehicles in poor condition) in gross vehicle weight (Scheuter 1998).

2.4 PAVEMENT BASED WEIGH-IN-MOTION SYSTEMS

Today there exist many pavement WIM systems all competing in a diverse and highly competitive market. As mentioned in section 2.1, these systems can be divided into LS-WIM and HS-WIM systems. The latter systems are not as accurate as the former, but they allow recording of all vehicles uninterruptedly.

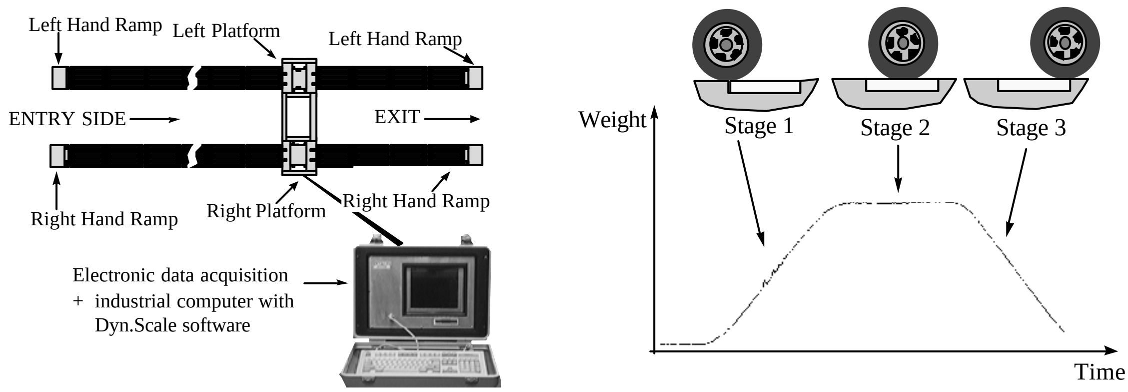
HS-WIM systems can be pavement or bridge based. Bridge WIM (B-WIM) will be discussed in later chapters. Pavement systems are sensors on or embedded in the road surface which record axle weights as a truck travels across the sensor at normal highway speeds. Their accuracy levels are not as good as low-speed systems, and they depend on the quality of the sensor, site location and approach. These WIM sensors can be divided into two categories according to their width: Bending plate and strip sensors. Unlike bending plates, the width of a strip sensor only covers a portion of the whole tyre. Hence, the wheel load is estimated from integration of the signals corresponding to the parts of the wheel acting on the strip at each instant. These sensors are sensitive to factors such as truck dynamics, road unevenness and temperature, which must be taken into account during the calibration of a WIM system. Recent developments show that the estimate of the static axle weights can be improved by combining an array of individual sensors. This procedure, known as Multiple-Sensor WIM (MS-WIM), is reviewed in the last sub-section.

2.4.1 Low-speed WIM

LS-WIM systems are commonly weighing scales which utilise strain gauges or load cells. These systems provide the high level of accuracy needed for enforcement or road pricing. They are based on the same principle as static weighing. Vehicles must also be taken aside by the police towards an area beside the roadside. However, vehicles are weighed while driving at a speed about 10 km/h over the system, and this makes possible the weighing of about ten times as many vehicles as static weighing. They can be portable or fixed. The fixed systems are based on platforms mounted in an excavation. The weighing platform should be longer (30 m) than for static weighing (15 m). The full plate LS-WIM maximum permissible error band is between 1 and 5%. 1% relates to a perfect fixed installation with vehicles in good shape, and 5% to a good mobile system with access ramps on an average site and vehicles in poor condition (Scheuter 1998).

Portable system

Portable LS-WIM systems are installed on a flat area with a ramp approach as illustrated in Figure 2.3.



(a) Portable low-speed system by Captels

(b) Recorded signal during the passage of an axle across the scales

Figure 2.3 – Low-speed WIM systems (after Dolcemascolo et al. 1998)

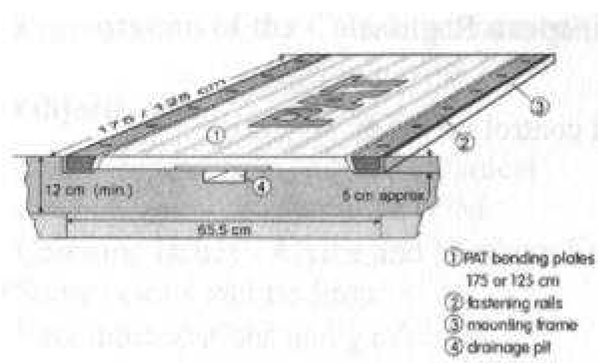
Through different tests, the need has been proven for a long ramp prior to the scales to avoid dynamic effects induced when an axle mounts the system. The ramp length after the scales should be greater than the axle spacing between extreme axles, to avoid oscillations induced when the first axle passes off the ramp. A distance of 30 m before the approach ramps is also required. It follows that the total site should be at least 70 to 80 m long.

There is also an influence of speed on final results: loads may be overweighed at speeds lower than the ideal speed and underweighed at higher speeds. This problem can be overcome through a software modification. This portable version could meet the requirement for overload enforcement with a careful implementation and an increase in its reliability (Dolcemascolo et al. 1998).

The semi-fixed version is based on scales installed in excavations, but without a ramp approach. This system should satisfy the required accuracy without the inconvenience introduced by the ramp.

2.4.2 High-Speed Bending plate

High-speed WIM systems collect continuous data that can be used for statistical purposes, while minimising traffic disturbance. One of the most accurate systems is the Bending plate. These plates are made of steel or aluminium with strain gauges attached to the underside. The width of a plate is big enough to take a complete pair of wheels. Figure 2.4(a) shows the dimensions and components of a commercially available bending plate system, and Figure 2.4(b) illustrates a bending plate after installation.



(a) Bending plate by PAT (after Hallström 1999)

(b) Bending plates at Zurich test site[6]

Figure 2.4 – Bending plate WIM

2.4.3 High-Speed Strip Sensors

Strip sensors are high-speed WIM systems. They provide a more economical solution than bending plates, though their results are not generally as accurate. Strip sensors available today are capacitive, piezoelectric, quartz and fibre optic. The physical properties of each type will govern their performance under real traffic loading. Sophisticated algorithms are being developed to improve overall accuracy through the use of an array of strip sensors (MS-WIM).

Preparing the highway and placing the sensors is one of the most expensive elements of any WIM system and it also has a major impact on their final performance. Some sensors can be placed on the roads while others must be installed in a slot cut in the road surface and bonded in place using epoxy resin. These weighing sensors are usually used in combination with inductive loops or piezoelectric axle detectors that provide data on vehicle speed, chassis height and length.

Inductive loops

Loop detectors operate on the principle of electrical inductance, the property of a wire or circuit element to induce currents in isolated but adjacent conductive media. An electromagnetic field is generated around the loop when driving an alternating current through the wires. When a car passes through the field, it absorbs electromagnetic energy and simultaneously decreases the inductance and resonant frequency of the loop, which indicates the presence of a vehicle.

Capacitive systems

Capacitive systems consist of two or more parallel steel plates separated by a dielectric material encased in a rubber housing. As a wheel passes over the sensor, the upper plates deflect and the change in capacitance is proportional to the applied load. Figure 2.5(a) shows the installation of an array of capacitive sensors.

Piezoelectric systems

Piezoelectric sensors are made of a conductor surrounded by highly compressed pressure-sensitive piezoelectric material. An increase in pressure on the sensor provides a measurable voltage that can be used for vehicle detection, speed detection, vehicle classification and weighing. A charge is only generated when the forces are changing, so if a constant force is applied, the initial charge will decay.

Quartz crystal

The quartz sensor is based on a change of its electrical properties as a function of the applied stresses. The quartz elements are mounted in a specially designed aluminium extrusion. This section maximises the transfer of vertical load onto the sensing elements whilst preventing lateral pressures from influencing the measurements (Hoose & Kunz 1998). An example of this system on site is shown in Figure 2.5(b).

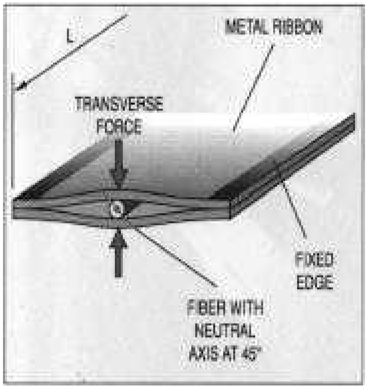
(a) Capacitive strip multi-sensor array at Abingdon, UK

(b) Quartz and Piezo-ceramic sensors at Zurich test site

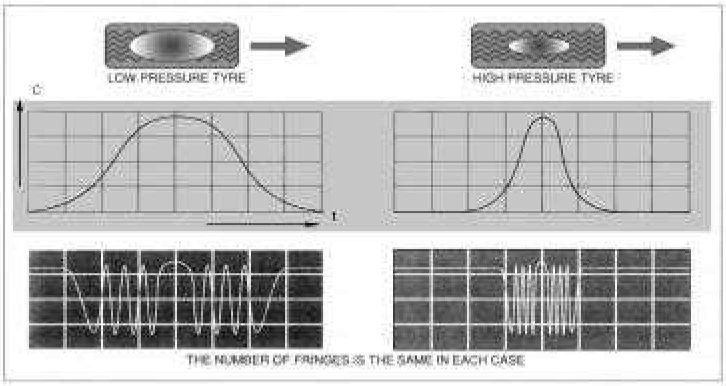
Figure 2.5 – Installation of strip sensors[6]

Fibre Optic

A fibre optic sensor ribbon is made of two metal strips welded around an optical fibre as illustrated in Figure 2.6(a). The sensor principle uses induced photoelastic properties in glass fibre under a vertical compressive force. This induces the separation in two propagating modes: a vertical faster mode and a slower horizontal mode. The pressure transferred to the optical fibre creates a phase shift between both polarisation modes, which is directly related to the load on the fibre. Some of the advantages of fibre optic sensors include good operation from stationary vehicles to speeds over 40 m/s, low temperature dependence, electromagnetic immunity, easy installation, no requirement for electric supply and data processing in real time. Field tests indicate a good behaviour of sensors in a two year test with heavy traffic (Caussignac and Rougier 1999). This technology can evaluate parameters such as tyre pressure (Figure 2.6(b)), vehicle acceleration or suspension condition.



(a) Scheme of the sensor element



(b) Weight signature and pressure tyre influence for an identical weight at different pressures

Figure 2.6 – Fibre Optic Technology (after Caussignac et al. 1998)

2.4.4 Calibration of Pavement Systems

The European specification on WIM gives guidelines on how to calibrate Pavement WIM systems in relation to the calibration method, site, vehicles, loading conditions, speed and number of runs. The calibration of a WIM system with respect to the static load, is commonly based on the hypothesis of proportionality between the static gross vehicle weight of the calibration trucks and the sum of the dynamic axle loads measured in motion by the system. This constant of proportionality is the calibration factor (C), which can be obtained by minimising the mean square error between dynamic and static loads. Equation (2.1) shows how this factor is calculated (COST323 1997).

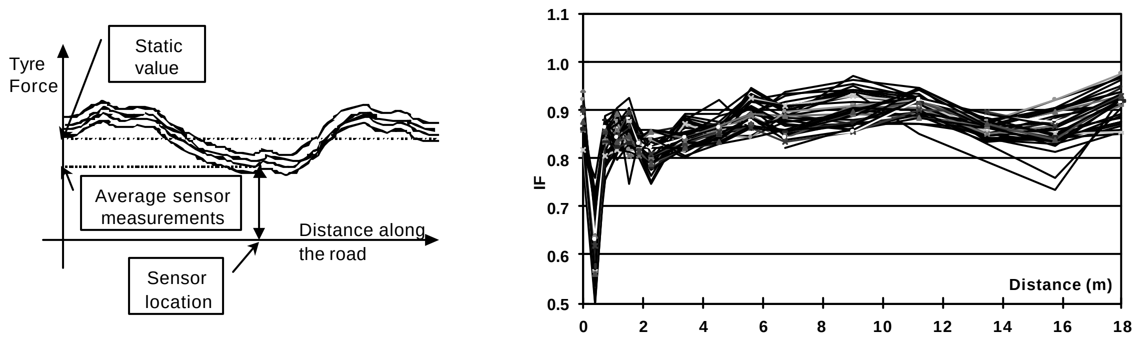
$$C = \frac{\sum_i n_i}{\sum_i \left[\frac{\sum_{j,k} Wd_{ijk}}{Ws_i} \right]} \qquad \begin{array}{l} i=1,\ldots \textit{number calibration trucks} \\ j=1,\ldots \textit{number runs} \\ k=1,2\ldots \textit{number of axles} \end{array} \tag{2.1}$$

where Ws_i is the static gross weight of the calibration truck i, n_i the number of runs of truck i, and Wd_{ijk} the measured dynamic load of axle k for run j in truck i.

If used for enforcement, calibration will have to be improved removing almost all the bias on axle and gross vehicle weights. However, there are difficulties with a calibration based on static axle weights due to the dynamic character of the applied wheel load. The deviations from the static value will depend on the truck dynamics, speed and the road profile, and so, even very smooth roads and good suspensions induce a variation of at least $\pm$10%. Therefore, some systems are sensitive to temperature variations or need a new calibration after a certain period of time. These aspects and some other interesting features are briefly reviewed in the following subsections.

Spatial Repeatability

Jacob and Dolcemascolo (1998) show how the maximum ratio of dynamic impact force to the static weight (maximum *IF*) may easily reach 1.25 to 1.5 on a rather smooth pavement, and up to 2.0 (air suspension) or 2.5 (steel suspension) on a rough pavement. This is the motivation of the site classification proposed in the European specification on WIM (COST323 1997). If the same vehicle passed the same road path several times at the same speed, the total applied axle force would present a similar pattern in a phenomenon known as spatial repeatability (Figure 2.7(a)). If one vehicle passed several times at different speeds the curves are more scattered as shown in Figure 2.7(b).



(a) Pattern of spatial repeatability (b) Patterns of spatial repeatability for 40 passes at all speeds (after Jacob and Dolcemascolo 1998)

Figure 2.7 – Effect of spatial repeatability on the calibration of a single WIM sensor

The curves become more scattered if using more than one only vehicle. If different axles of different vehicles travelled along the same road profile at different speeds, the tendency to present a similar load pattern is known as statistical spatial repeatability (O’Connor 1996, O’Connor et al. 1999). This phenomenon is explained by the averaging of the individual vehicle characteristics while the pavement effect becomes dominant as the size of the sample increases. The effect of spatial repeatability can be minimised by MS-WIM systems that obtain results at different road sections.

Instrumented trucks

The instantaneous dynamic axle force measured by an instrumented truck and the value measured by a WIM system can be compared for a more accurate calibration. This possibility was studied by VTT (Technical Research Centre of Finland) as part of the WAVE project (Huhtala 1999). Dynamic wheel forces are matched to the WIM systems using an electric eye to detect reflective tapes glued across the road lane. Figure 2.8 shows the axle forces measured by a WIM system (bending plate) versus the instantaneous dynamic wheel measurements.

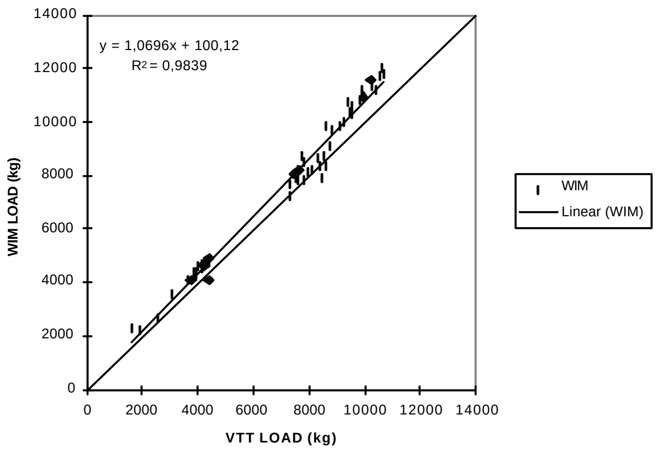


Figure 2.8 – Dynamic axle loads measured in the vehicle and by a WIM system (after Huhtala 1999)

The instrumented vehicle is a 3-axle rigid truck with a rear tandem, and axle static weights: 6000, 8800 and 7200 kg. The static values in all the runs of the figure are the same, but the dynamic loads are different due to changes in speed. The scatter is introduced by inaccuracy of the WIM system and/or the instantaneous wheel load measurement.

Environmental conditions

Many narrow strip sensors are sensitive to temperature. Further, they are affected by variations of the resin modulus and pavement support in which they are fixed. This is why they need periodic calibrations. An automatic self-calibration procedure was developed to avoid this inconvenience (Stanczyk & Jacob 1999). This procedure is based on the identification of characteristic vehicles from the traffic. Then, typical weights are adjusted to target values of these characteristic vehicles from a statistical knowledge of traffic.

Stanczyk (1999) points out mean bias in the determination of static axle load for several WIM sensors due to load transfers from axle to axle for different truck categories. This bias is related to the vehicle dynamics and driving conditions, the local road conditions and the WIM sensor and system response. For example, WIM systems generally under-weigh first axles which could be due to aerodynamic and torque effects. As result, some corrections by axle to reduce the mean bias show a promising improvement in calibration procedures (Tierney et al. 1996).

2.4.5 Multiple-sensor WIM

Up to this, individual pavement sensors have been discussed. One sensor records the instantaneous load applied by a tyre, and a significant error in the determination of the static weight could take place as a consequence of the dynamic load oscillations. Different procedures have been used to reduce these errors based on the use of multiple sensors at different road sections: A simple average of all the sensor readings, a signal reconstruction method, and a maximum likelihood method have been tested and a neural network approach is under development. These procedures are described below.

Simple Average

Dolcemascolo & Jacob (1998) estimate static axle loads as the spatial mean of the impact forces measured over a sufficiently long path. Sensors are placed at uniform spacing to avoid any bias due to spatial repeatability, and they should cover a length in excess of the longest wavelength of the impact force signal. Axle loads are estimated by the average of the individual measurements of the sensors considered. The following formula (Cebon 1999) is used for the calculation of the optimum spacing (d) between sensors:

$$d = \frac{2V(n-1)}{fn^2} \tag{2.2}$$

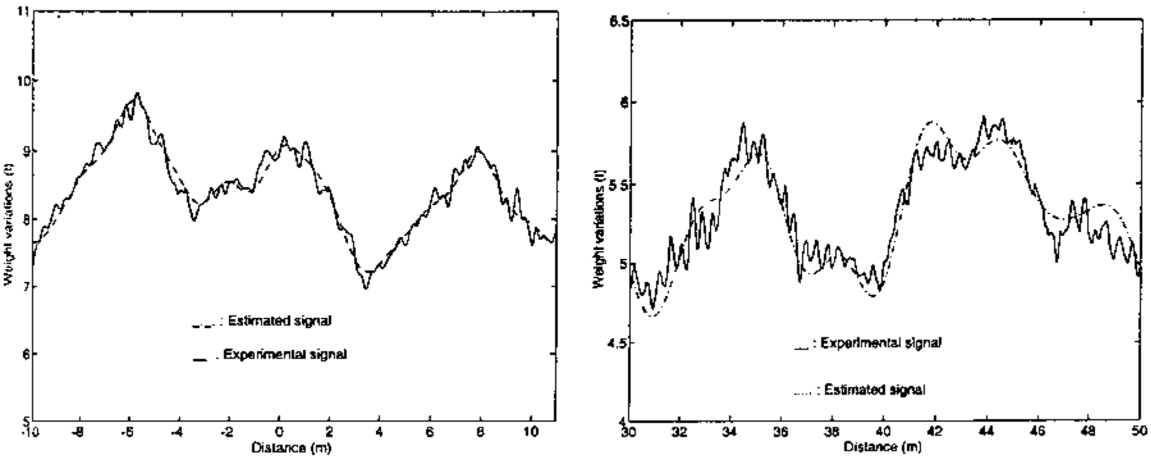
where V is the mean traffic speed (m/s), n the number of sensors and f the mean bounce motion frequency. This formula was obtained by minimising the average quadratic error between the real and the estimated static weights computed by the average method and uniformly spaced sensors, with the assumption of random distribution of speed and frequency around their mean value.

An increase in the length of the sensor array has a very strong influence on the accuracy of gross vehicle weight, as the averaging procedure smoothes the bias resulting from spatial repeatability.

Signal Reconstruction and Kalman Filtering method

A method for the estimation of the static axle load based on the reconstruction of its dynamic variation is proposed by Sainte-Marie (1998). The continuous signal representing the dynamic axle weight is generated from the discrete measurements given by each sensor through the use of different functions: trigonometric polynomials, non-harmonic Fourier series and cardinal series. Figure 2.9 represents the re-constructions from two simulated instrumented vehicles.

Static axle weight is estimated as the average of the reconstructed signal along a certain length. This length depends on the rolling and bouncing frequencies of the vehicles which are obtained through extended Kalman filtering. Further developments involve the consideration of load transfer from one axle to another, the road profile and truck interaction and the use of functions based on the eigenmodes of simplified vehicle models.



(a) Canadian truck with non-noisy measurements

(b) German trailer noise to signal ratio: 10%

Figure 2.9 – Reconstruction carried out with 13 samples (after Sainte-Marie et al. 1998)

Maximum likelihood technique

A probabilistic method based on the Maximum Likelihood estimator has been developed by a transportation research group in the University of Cambridge (Stergioulas et al. 1998, Cebon 1999). The Maximum Likelihood method adjusts the signal model parameters by maximising the probability that the estimated data is the correct one. Through the knowledge of the main oscillation modes of dynamic tyre forces, the method proposes two main generic vehicle models:

- A quarter car model representing about 80% of truck suspensions. These trucks have a main frequency corresponding to a body-bounce mode in the range 1.5-4.5 Hz. The vehicle model can be idealised by a constant (static weight) plus a single sine wave of low frequency. The model has 4 unknown parameters: static weight, and amplitude, frequency and phase of the sine wave. Hence, a minimum number of 4 sensors is necessary for the solution of the Maximum Likelihood calculation.
- A walking beam model representing about 20% of truck suspensions. These trucks have two significant frequencies. One corresponds to the body-bounce, while the other corresponds to an axle hop mode in the range 8-15 Hz. A constant plus two sinusoidal components of low and high frequency can approximate this model. A minimum number of 7 sensors is required in this case.

2.5 ACCURACY OF WEIGH-IN-MOTION SYSTEMS

The performance of a WIM system is best evaluated by testing. The quality of the results, performance and durability of the different systems can be best compared under the same environmental and testing conditions. Only long-term tests (over a full year) allow the WIM systems to be subjected to all seasonal conditions and their durability to be assessed. Test vehicles make repetitive runs over the test site, and the resulting WIM data is processed and compared with static weight measurements of the same vehicles. Alternatively, vehicles taken randomly from the traffic are weighed statistically and used to assess the WIM system accuracy.

The analysis of WIM results and accuracy classes defined here refers to the European specification for WIM of road vehicles (COST 323, 1997). The COST323 specification, like the ASTM standard, applies a statistical definition of accuracy using confidence intervals. Other recommendations dealing with legal applications, such as the draft OIML (**O**rganisation **I**nternationale de **M**étrologie **L**égale) standard, define accuracy as maximum permissible error (Dunmill 1998).

The COST323 specification considers six classes of accuracy, A, B, B+, C, D and E with A being the most accurate. The accuracy class of a particular site is obtained from the confidence interval width (d), mean (m), and standard deviation (s), of the errors in weighing a sample of n trucks. If the probability (p) of measuring results within a certain interval exceeds a specified minimum (p_o), this WIM system will comply with a given accuracy class. This minimum depends on the number of trucks, the duration of the test and type of test carried out. There are three kinds of environmental conditions: (I) repeatability, for a short test over a few consecutive days and the same climatic conditions, (II) limited reproducibility, for a test carried out over several days or weeks within the same season, and (III) full reproducibility, for a long term test over a year or more. There are four criteria for the type of test plan carried out during that time: (r1) full repeatability, if only one truck is used, with one load and speed, (r2) extended repeatability, if only one truck is used, but with several loads and/or speeds, (R1) limited reproducibility, if a small set of trucks are used, and (R2) full reproducibility, if a large set of trucks from the traffic flow are used, each of them passing only once on the WIM system. Appendix B gives a more detailed explanation of the statistical issues involved in this COST323 accuracy class classification.

The results presented herein show the great influence of the quality of the site on the accuracy of any WIM system. The best accuracy class met by a HS-WIM system on a trafficked road was B(10) on an excellent site. Best systems could not get an accuracy better than C(15) in average or good sites (Jehaes 1999a).

2.5.1 Long Term Test on Urban Road (Zurich, 1993-1995)

The first major European test took place on an urban road in Zurich (Blab et al. 1997, Jehaes 1999a). Various systems available on the commercial market were tested together. These systems included capacitive strips, piezo-ceramic strips, bending plates, piezoquartz strips and piezopolymer strips. The test had some limitations due to the reduced number of vehicle types, low traffic flow and speed in the particular urban conditions, the fact that only gross vehicle weights were considered and the rather poor pavement conditions – class III site –. Best results were obtained by a bending plate system that achieved class C(15) as expected in a class III pavement. It revealed the strong need to improve the understanding of WIM system performance and influence of different environmental factors in further trials[7].

2.5.2 Alpine Tests (Switzerland, 1995-1998)

Two WIM systems were installed in different tunnels in main alpine transit routes in 1995: 4 capacitive strips in each direction in a class I site, and two bending plates in each direction in a class II site. Both systems were exposed to tunnel air conditions, use of salt and high concentrations of corrosive substances. The capacitive strips failed and were replaced by 2 piezoquartz strips, while the bending plate system survived over three years. The results in full reproducibility conditions (R2) were class C(15) for the capacitive and piezoquartz strips in one direction, and E(30) and D+(20) respectively in the other direction and environmental repeatability conditions (I). The strip sensor system in one of the directions was affected by the curvature of the road. Bending plates were in class B(10) and C(15) respectively for the north and south directions in limited reproducibility conditions (II) during three years (Jehaes 1999b).

2.5.3 Weigh In Motion Experience in Belgium (1994-1998)

Henau (1998) reports about the testing of four WIM systems installed on a motorway interchange (E42 and E411) at Namur, Belgium in July 1994. The systems were composed of inductive loops and a glass-fibre reinforced bar-type piezoceramic weight detector. E42 has a rigid structure comprising a continuous reinforced concrete pavement, and E-411 has a semi-rigid structure with a bituminous concrete pavement on top of a concrete base. These sites conform to classes II and III respectively. Accuracy class D(25) was obtained by the best system in limited reproducibility conditions (R1) and environmental repeatability conditions (I). This accuracy class is in accordance with a site class from II to III. However, all systems in the fast lane were in class E for full repeatability conditions (r1). The WIM system was affected by the presence of a local underpass some tens of metres upstream that induced some high vehicle dynamics.

2.5.4 Portable and Multiple-Sensor WIM systems trial (Trappes, 1996)

A short trial took place near Trappes, France in June 1996. A preliminary draft of the COST323 European Specification on WIM was applied to the results. A MS-WIM system composed of piezo-ceramic strip sensors was installed in this class II site.

Sainte-Marie et al (1998) report on results on isolated axles by using the signal reconstruction technique referred to above (Axles of an axle group were not considered as their more complex dynamic behaviour is under study). In full reproducibility conditions (R2) and a sample of 34 five-axle vehicles (2 axles in the tractor and 3 in the trailer) from the traffic flow, the reconstruction technique based on 6 or 12 sensors achieved class B(+7) for the first two axles. For the same sample, a simple mean average leads to class B(10) with 5 sensors and B(+7) with 13 sensors. In the same scenario, Dolcemascolo and Jacob (1998) reported a study on MS-BWIM based on an averaging technique and uniform sensor spacing. Conclusions reveal that a number of sensors above 7-10 should increase the robustness of the results, rather than achieve a higher accuracy. Better accuracy can be achieved through improvements of the individual sensor performances.

Dolcemascolo (1999) evaluates the performance of the three different MS-BWIM approaches presented in 2.4.5 with the following conclusions:

- The Likelihood method based on two sine waves (LK2) is less reliable than the others.
- The Simple Average (SA) and Likelihood method based on one sine wave (LK1) have a good robustness and are less sensitive to noisy sensors.
- The accuracy of SA and LK1 methods are very similar.
- The signal reconstruction (SR) and LK2 method need more parameters and they are more sensitive to the number of sensors.
- Class A(5) was only obtained for single axles of two axle rigid trucks and a sub-array of 13 sensors.
- Accuracy of SR, LK1 and LK2 methods should improve with less noisy sensors.

During this trial, four portable WIM systems (3 capacitive mats and 1 capacitive strip) were also tested. All these systems felt into classes from E(30) to E(60). Their inaccuracy was mainly due to the dynamic impacts induced in the axles of a group by the thickness of the sensors laid on the road.

2.5.5 The European Test Programme (1996-1998)

The COST323 action conducted a large-scale series of trials, the European Test Programme (ETP) (1997-1998), to evaluate the accuracy and durability of WIM systems. The main general objectives of the ETP were (Henau and Jacob 1998):

- Evaluation of WIM systems in various environments and over long term periods.
- Comparison of the WIM system performances with the requirements of the draft European specification and the users' needs and requirements.
- Acquisition of data for research and statistical studies.

These tests were carried out in two different environments: the Cold Environment Test (CET) in a main road in Northern Sweden (Luleå) and the Continental Motorway Test (CMT) in a heavily trafficked motorway in Eastern France. The first test site is related to the performance and durability of WIM systems in cold climates under harsh conditions (frost heave of pavement, mechanical impact of snowploughs, etc.), while the second site is more concerned with aggressive traffic conditions, representative of main European routes. The CET was the most significant large-scale trial ever organised in Europe and the results are summarised below.

The Cold Environmental Test

The Swedish National Roads Administration (SNRA) managed the tests in Sweden, and the Belgium Road Research Centre (BRRC) and Institute of Road Construction and Maintenance in Austria (ISTU) analysed the accuracy of the results. The traffic density at the site is 350 heavy lorries per day in each direction, and their speed limit is 80 km/h. The road has two lanes and a class II profile according to the European WIM Specification. The WIM systems being tested were: one Bridge system and four high-speed systems embedded in the pavement: a piezoceramic nude cable, one prototype combination of two piezoquartz strip sensors, a bending plate based on strain gauges, and a 'bending beam' prototype.

Jehaes and Hallström (1998) show the accuracy of results and their evolution over a complete climatic year. During each test, two types of population were examined: at least one calibration vehicle with several loads and speeds, and some post-weighed vehicles selected from the general traffic flow at random. Some of the systems did not work properly and all became somewhat less accurate during the winter period with temperatures below –30°C or spring due to the large variations of temperature in 24 hour periods. All of them recovered their initial accuracy during the following summer. Only the system based on quartz crystal piezoelectric bars was able to achieve an accuracy class C(15) for any period and vehicle test. The post-weighed vehicles are analysed in full reproducability conditions (R2), and the test vehicles in limited reproducability conditions (R1). The results of this system in full environmental reproducability conditions (III) are shown in Tables 2.1 and 2.2. In these accuracy tables, the first columns represent the statistics of the relative error *(Wd-Ws)/Ws*, where *Wd* is the predicted weight and *Ws* is the static weight, *n* is the number of data, *ide is* the percentage of correctly identified vehicles, *m* the mean and *s* the standard deviation. In the remaining columns, *class* represents the accuracy class for each criterion class, δ the tolerance of the retained accuracy class, δ_{min} the minimum width of the confidence interval for π_o, π_o the required level of confidence, and π the level of confidence of the interval [-δ,δ].

Table 2.1 – Accuracy classification for general traffic during one complete year

(**n**: Total number of vehicles; **Ide**: Percentage of vehicles correctly identified by the system; **m**: mean; **s**: Standard deviation; $\mathbf{p_0}$: level of confidence; **d**: tolerance of the retained accuracy class; $\mathbf{d_{min}}$: minimum width of the confidence interval for π_0; **p**: Level of confidence of the interval [-δ,δ])

	Relative error statistics					**Accuracy calculation**				
Quartz piezo – general traffic	**n**	**Ide**	**m**	**s**	$\mathbf{p_o}$	**Class**	**d**	$\mathbf{d_{min}}$	**p**	**Class retained**
Criterion		(%)	(%)	(%)	(%)		(%)	(%)	(%)	
Single axle	750	90	0.29	10.25	92.0	**C(15)**	20.0	18.7	93.9	**C(15)**
Axle of group	1721	91	1.41	10.02	92.4	**B(10)**	20.0	18.5	94.6	
Group of axles	838	91	1.41	7.33	92.0	**C(15)**	18.0	13.6	98.1	
Gross Weight	460	90	0.92	7.53	91.6	**C(15)**	15.0	13.9	94.0	

Table 2.2 – Accuracy classification for test vehicles during one complete year

(**n**: Total number of vehicles; **Ide**: Percentage of vehicles correctly identified by the system; **m**: mean; **s**: Standard deviation; $\mathbf{p_0}$: level of confidence; **d**: tolerance of the retained accuracy class; $\mathbf{d_{min}}$: minimum width of the confidence interval for π_0; **p**: Level of confidence of the interval $[-\delta,\delta]$)

	Relative error statistics					**Accuracy calculation**				
Quartz piezo - test vehicles	**n**	**Ide**	**m**	**s**	$\mathbf{p_o}$	**Class**	**d**	$\mathbf{d_{min}}$	**p**	**Class retained**
Criterion		(%)	(%)	(%)	(%)		(%)	(%)	(%)	
Single axle	361	83	2.58	5.48	93.7	**B(10)**	15.0	11.9	98.3	**C(15)**
Axle of group	845	95	5.19	10.29	94.2	**C(15)**	25.0	22.5	96.6	
Group of axles	368	95	5.40	6.42	93.7	**C(15)**	18.0	16.0	96.8	
Gross Weight	310	87	3.93	5.21	93.6	**C(15)**	15.0	12.5	97.7	

The bending plate obtained a final accuracy of D(25) (conditions R2, III) due to a lack of temperature compensation in the winter period. The system used temperature compensation in the summer achieving D+(20). The other two WIM systems being tested were in class E.

The Continental Motorway Test

The objectives of this test were to evaluate WIM systems commercially available in Europe over a period of 12 to 18 months, and to compare their performance on a smooth pavement against the proposed requirements of the current European Specification on WIM. In addition, the reliability of sensors, electronic equipment and software were being monitored. The test was carried out by CETE de l'Est and the Laboratoire Central des Ponts et Chaussées (LCPC) in France. The site is situated on the slow lane of the A31 motorway between Metz and Nancy with international traffic of 40000 vehicles/day of which 20% are heavy vehicles. The pavement is classified as class I according to the European specification for WIM. The different typologies of weighing sensors being tested were four piezo-ceramic bars, a piezo-ceramic nude cable and a capacitive mat. Magnetic sensors and inductive-loops were used for axle detection. Results are reported by Stanczyk and Jacob (1999).

The capacitive mat and one of the piezo-ceramic systems achieved class B(10), another two systems class C(15), and the other two class D+(20) and class E(30) in conditions of full reproducibility (R2) and environmental reproducibility (III). The results of the piezo-ceramic system are shown in Table 2.3.

Table 2.3 – Accuracy of the best system for all the pre-weighed traffic trucks

(**n**: Total number of vehicles; **Ide**: Percentage of vehicles correctly identified by the system; **m**: mean; **s**: Standard deviation; $\mathbf{p_0}$: level of confidence; **d**: tolerance of the retained accuracy class; $\mathbf{d_{min}}$: minimum width of the confidence interval for π_0; **p**: Level of confidence of the interval $[-\delta,\delta]$)

	Relative error statistics				Accuracy calculation				
Piezo-ceramic	**n**	**m**	**s**	$\mathbf{p_o}$	**Class**	**d**	$\mathbf{d_{min}}$	**p**	**Class Retained**
Criterion		(%)	(%)	(%)		(%)	(%)	(%)	
Single axle	1485	-1.77	8.02	92.3	B(10)	15.0	14.91	92.4	**B(10)**
Axle of group	1328	2.67	8.49	92.2	B(10)	20.0	16.18	97.2	
Group of axles	588	2.63	5.97	91.8	B(10)	13.0	11.85	94.5	
Gross Weight	686	0.61	4.60	91.9	B(10)	10.0	8.46	96.2	

The capacitive mat achieved B+(7) under the criterion of axle of a group. However, this system failed due to the presence of humidity in the link cables and in the mat and it had to be replaced twice along the test. Temperature changed during the tests in the different seasons between 2 and 31ºC. The capacitive mat is insensitive to this variation while the piezo-ceramic bars corrected well through automatic self-calibration.

2.6 APPLICATIONS OF WEIGH IN MOTION DATA

National Road Administrations are the main users of WIM. There are different fields where governments can apply WIM data. I.e. development of design codes for pavements and bridges, assessment of traffic aggressivity for a pavement, road and traffic management, enforcement and road pricing.

And the requirements in accuracy of WIM systems will vary depending on their final application:

- Legal purposes: Better accuracy than 5% with respect to the static weights is required (Jacob and Stanczyk 1999). Low-speed WIM can provide accuracy results of A(5) and even better taking precautions during installation and operation of the system.
- Traffic statistics, traffic and road monitoring, and road infrastructure and design: High-speed WIM can achieve accuracy in the range of 10 to 25% which is fully accepted in these applications.

2.6.1 Pavements

The road network is one of the largest investments of any country. Design procedures require the prediction of the total traffic that the roads will carry over their design lives. The service lifetime and periodic maintenance will depend on the deterioration of the road structure, progressively damaged by heavily loaded vehicles. Thus, WIM data can lead to improvements in maintenance methods and more reliable pavement design.

Design

There is often assumed to be a linear relationship between damaging effect on the road structure and the number of repetitions, but the relationship between magnitude and damaging effect is a power law with a high exponent. The linear relationship depends on the type of axle (single, tandem or tridem axle) or vehicle and the pavement material and structure. The exponent depends on the pavement type. This exponent is often assumed to be 4, so a small increase in axle weight involves a high increase in road wear. WIM data can save material by providing a better knowledge of the load histogram.

Serviceability or driving comfort by the user, is a subjective concept which is difficult to evaluate. However, pavement design methods such as AASHTO give guides based on a specific total traffic volume and a minimum level of serviceability along a certain period. When the level of serviceability decreases below a certain value, overlaying or re-paving is deemed necessary.

It can be seen that the evolution of serviceability is difficult to predict, and the use of WIM systems for preventing overloaded axles can prolong the pavement life cycle.

Influence of WIM errors

Data from WIM measurements can be used to estimate the magnitude of axle loads and the number of repetitions. Collop et al (1998) have studied the effects of different types of WIM errors when estimating cumulative traffic for a design life:

- Calibration error, due to adjustments made every six months of any drifts in the WIM measurements.

- Random sensor error, due to the inaccuracy of the WIM sensors that might introduce random errors into the measurement.
- Errors due to differences between instantaneous dynamic and static loads

WIM systems must be re-calibrated with vehicle(s) of known axle loads. The impact factor (*IF*) is measured at each run and the mean of all *IF*'s is used to adjust the sensor calibration factors. The relative difference in mean *IF* between consecutive calibrations is known as the calibration error. The difference in mean *IF* indicates a drift in the WIM system, but it is often not possible to determine if this drift took place gradually or suddenly over a short period of time.

Calibration data from 13 WIM sites resulted in an average mean calibration error between 1 and 6% depending on the manufacturer, standard deviation of the calibration error of about 11% and random sensor plus dynamic load effect approximately 11%. If using a 4^{th} power law, these errors result in an over-prediction of 40% in the design traffic, and an increase in the pavement thickness of between 10 and 20 mm.

Future requirements

An extension on the information supplied by traditional WIM technology is recommended to predict rutting in upper layers, ravelling and cracking (Caprez 1998, George 1999). For example:

- Lateral position of the passing wheels, contact pressure and frequency of loading which are important for the use of visco-elastic pavement models.
- Vertical contact pressure and horizontal contact stresses to prevent deterioration mechanisms in upper layers.
- Type of tyre wheel: Rut is deeper under a single tyre wheel than under twin wheels.
- Road safety authorities have a great interest in data on tyre pressure to detect under-inflated tyres that could be the cause of accidents.
- Width of the tyre, contact area, pavement temperature.

2.6.2 Bridges

WIM data can be applied to different fields of bridge engineering such as load models, dynamic impact, assessment, fatigue and monitoring.

Load Models

A sub-committee of COST323 has made a significant contribution to the articulation of the Bridge applications of WIM (O'Brien et al. 1998a). One of the objectives of this sub-committee was to review the traffic load model specified in the Eurocode, EC1, Part 3. This model is based on traffic statistics collected at various WIM facilities. As traffic loads were found to vary significantly between different sites, the site with the highest loading was initially chosen as a basic reference to design a conservative main load model. This WIM data is used to simulate traffic flow over a wide range of bridge forms and spans in order to determine characteristic load effects corresponding to a return period of 1000 years.

Extrapolations of the extreme load effects were performed under the assumption that the load effect behaves as a stationary Gaussian Process. Rice's probability distribution function assumes a Normal tail which governs the extrapolation. Under this hypothesis, the tails histograms of level crossings of the load effect obtained from WIM records are fitted to the Rice function. This function has a Normal tail that governs the extrapolation for minimal or maximal effects for a given return period. The final basic load model should reproduce these load effects as closely as possible. Newer WIM data shows less variance due to recent improvements in the accuracy of WIM systems. This has leaded to a re-assessment of Eurocode 1, Part 3 (O'Connor et al. 1998).

The Eurocode allows correction factors on the main model specified above depending on the local traffic conditions of a country and road class. This correction requires the collection of axle weights and spacings (plus vehicle speed and inter-vehicle spacing in dual carriageways) from a number of representative sites over a sufficient period of time. Seasonal variations should also be taken into account.

A design traffic model for bridges with spans in excess of 200 m is needed in most design codes, including Eurocode 1, Part 3. The traffic load combinations to be considered include:

- An equivalent uniformly distributed load for each individual lane (EUDL). This EUDL can be modelled for each lane from the application of WIM data.
- A group of concentrated loads simulating a vehicle model to evaluate local effects. These concentrated loads can also be obtained from information on axle loads provided by WIM data.
- Exceptional vehicles in excess of 100 tonnes, which depends on policy issues.

Dynamic impact

A dynamic impact factor represents the difference between the total traffic effect to which a bridge may be subjected and the purely static effect. This total effect differs from the static one due to the dynamic interaction between bridges and vehicles.

Dynamic impact factors used in the design of short span bridges are usually very conservative as proven in different simulation studies. A certain static load can have a total effect after dynamic amplification in excess of a greater static load with a lesser dynamic amplification factor. The worst loading case in these bridges is generally associated with a two-truck event, but its dynamic impact factor can be less than the one corresponding to a smaller load. Thus, WIM systems provide a tool for collecting information on the relationship between static and dynamic loads.

O'Brien et al (1998) underline the need for simulations and/or Bridge WIM measurements of the dynamic traffic load effects with a focus on the load cases which govern the limit states on a range of bridges.

Assessment

The use of site-specific traffic load models rather than design load models obviate the need for bridge strengthening or traffic restrictions. Bridges can be assessed using WIM records in a similar way to the derivation of the Eurocode traffic model. Crémona and Carracilli (1998) assess the added tensions induced by traffic effects on the cables of a cable stayed bridge and a suspension bridge through WIM systems installed on the bridges to derive the corresponding histograms. Regarding the safety of both bridges, ultimate design loads are larger than the extrapolated ones.

Fatigue

Fatigue damage is a function of the magnitude and frequency of the load effect cycles as well as the fatigue strength of the structure. The fatigue is studied through three different procedures: First, a simplified procedure will allow for the determination of whether maximum stresses are higher than a safe threshold value. If this is the case, more detailed approaches are necessary. These approaches are:

- Miner's law to quantify fatigue damage. WIM data is useful to implement the traffic loads with probabilistic methods.
- Fracture Mechanics to predict crack size based on the stress range history.

Fatigue lifetime is extremely sensitive to traffic loads, and WIM data is extremely valuable for the design and assessment of steel and composite bridges. It is also necessary to keep a WIM database to perform fatigue calculation taking into account the past loading history (Jacob 1998b).

Monitoring

WIM systems can be used to monitor traffic loading of bridges in real time. Data collected can provide information on the existing loads and if a maximum safe bridge load is reached, warnings, traffic lights or barriers could be activated to limit the traffic loading and protect the bridge. It could also lead to criteria for the need of bridge strengthening.

2.6.3 Road and Traffic Management

The efficiency of highway infrastructure can be increased with accurate data on vehicle types, speed, weight, traffic density or environmental conditions. Traffic management in real time allows the distribution of traffic flows in time and space, or warning to drivers of conditions on the road ahead when an incident has been detected. Other applications include:

- Detection of violation of reserved lanes.
- Effect of the percentage of slow vehicles on lane capacity.

- Management of rest areas.
- Tolling.
- Statistical information for studies on economy, traffic patterns, or relationship between traffic and air pollution or accidents.

2.6.4 Enforcement and Road Pricing

Overloading must be penalised to increase the safety of road transport, to ensure fair competition and to preserve the infrastructure. Therefore, the road contractor, who must guarantee the road conditions over a specified period, has the right to check that no overloaded axles are damaging the structure. Static weighing scales were unable to detect a significant proportion of these overloaded axles, but the use of WIM systems allows for an instantaneous check of all traffic without any disturbance to the road users. A dissuasive way to discourage overweight vehicles is by increasing enforcement activity. According to the Legal Metrology Division of the French Ministry of Industry (Marchadour 1998), the accuracy level required in a weighing system should fulfil the tolerances of class A(5) according to the European Specification on WIM (COST323 1997) or at least B+(7) for all criteria, and improvements should be proposed by the manufacturer to reach A(5) within a year. The system should alternatively be in class 5 of the OIML draft recommendation on WIM (Dunmill 1998), or at least in class 10, to be improved up to class 5 within a short time period.

WIM systems can also be used in road pricing if vehicle weights are taken into account in the tax system. This tolling can take place in two different ways (Doscemascolo and Jacob 1999, Jacob and Stanczyk 1999):

- Taxation according to the individual weight. Class A(5) or higher is required.
- ‘Shadow Toll’ procedure: Annual fee paid by the infrastructure’s owner to the road operator and those responsible of maintenance. This fee is adjusted as a function of real traffic measurements. Class B+(7) is required.

LS-WIM can be used for enforcement. At low and constant speed, vehicle bounce and load transfers due to drag or changes in acceleration are small. However, load transfers due to differences in height between the bogie axles on the weighing platform and the surrounding area are likely, and they should be minimised.

Newton (1998) suggests the use of transponders (electronic license plates) fitted to the vehicles that could transmit the information on the maximum permitted weights to the WIM system. These transponders could also incorporate a system whereby the driver could get messages sent to a weighing site for enforcement.

HS-WIM systems can be used for selecting vehicles for enforcement weighing, monitoring the level of overloading or automatic weight. Video can be used in combination with WIM systems for pre-selection of overloaded vehicles (WIM-VID). Dienst Weg-En Waterbouwkende (DWW) carried out a pilot project to investigate this possibility. Two types of WIM systems were tested: Bending plates that almost achieved class B(10), and piezoceramic sensors in class C(15), acceptable for pre-selection (Henny 1998). Weight information and a video picture of the vehicle are captured in a PC screen as illustrated in Figure 2.10. Overloaded axles and gross vehicle weights are shown in red if exceeding the limit. As a result, a wider range of vehicle types were selected and the efficiency of selected vehicles that were overloaded was raised from 46% without WIM to 96% with WIM (Van Dijk 1999).

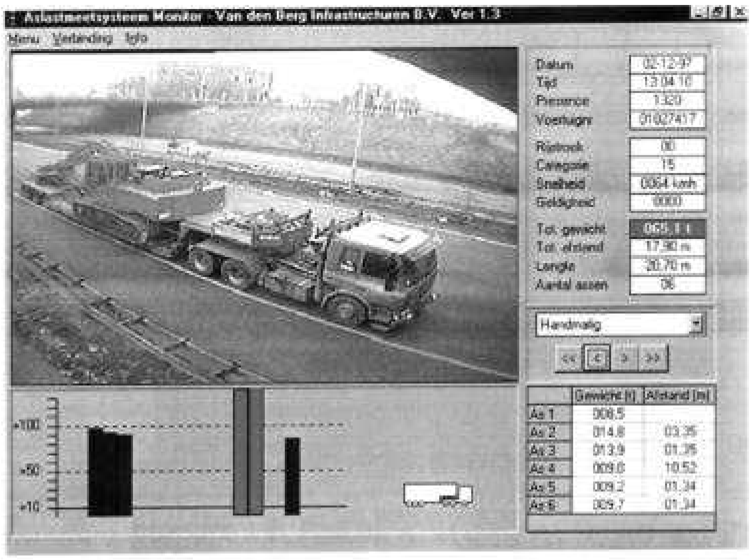


Figure 2.10 – Example of PC screen for pre-selection (after Henny 1999)

Figure 2.11 summarises the implementation of the ideas expressed above by a commercial system.

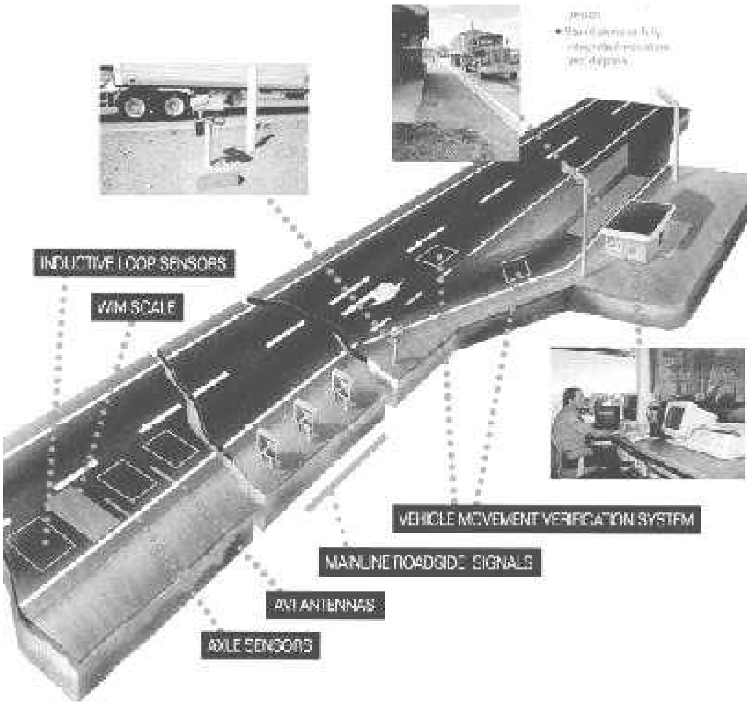


Figure 2.11 – IRD mainline WIM weigh station system[9]

Chou and Tsai (1999) have studied the possibility of using HS-WIM for direct enforcement. The required WIM accuracy for legal enforcement can be derived from the maximum allowable reduction in pavement service life and the maximum allowable rate of misjudged overloading. However, the accuracy of HS-WIM systems must still be improved before being applied with this purpose, except in countries where gross overloading is commonplace.

Further progress with regard to legislation on the maximum weight of vehicles for national transport is expected in the EU, particularly relating to harmonisation of maximum weight limits for both vehicles and axles. In the opinion of Missen (1998), the political attitude of the Member States in this field in the next millennium will come about as a result of two independent factors. Firstly, an increase in vehicles that operate to their national weight limits performing cabotage in another country. Secondly, the development of weigh-in-motion equipment to control the degree of vehicle overloading that occurs. This is an area where WIM is of major importance, as static scales are expensive, scarce and easily avoided by lorry drivers.