WAVE

Weigh-in-motion of Axles and Vehicles for Europe

4th Framework Programme Transport - European RTD project, RO-96-SC, 403

EXECUTIVE SUMMARY

by ***Bernard JACOB,*** *Laboratoire Central des Ponts et Chaussées*
and ***Eugene O'Brien****, University College Dublin*

1. ORIGIN, OBJECTIVES AND MEANS OF THE PROJECT

1.1 Origin of the project

In most developed countries, a large majority of freight transportation is made by road. Thus, a rapid increase in road traffic and a major expansion in the number and size of heavy goods vehicles have been recorded on European roads in recent years. Moreover, because of the strong competition between transport modes and companies, transportation management was improved, which has led to an increase in the numbers of fully loaded trucks and their gross weights. It is of particular concern that such heavy vehicles are aggressive on bridges and pavements and that a significant number of lorries are illegally overloaded. A new emerging demand for weight data concerns road pricing, as more and more countries are privatising the main highways.

Therefore, it is essential for road authorities to have at their disposal up to date and on-line measurements of axle and vehicle weights in order to: (a) improve knowledge of traffic for economic surveys, statistics and management, (b) collect reliable data as a background which supports the technical basis for pavement and bridge design and maintenance, (c) prepare the basis for legislation relating to road safety and fair competition in transport, leading to harmonisation of enforcement across Europe, and (d) provide government authorities with the information necessary for a harmonised tax system.

A shared-cost action COST 323 (**CO-**operation in **S**cience and **T**echnology) was initiated in 1992 within the framework of the COST-Transport programme to facilitate co-operation and the sharing of experience on Weigh-In-Motion (WIM) between member countries. The management committee published an extensive report on Needs and Requirements for WIM in Europe (COST323, 1997), which clearly pointed out the state-of-the-art of development of WIM networks and systems throughout Europe and their applications. Moreover, the newly developed European Specification for WIM (COST 323, 1999) provides all the definitions and tools necessary to assess the accuracy of WIM systems with respect to their real performance, and the requirements appropriate to particular applications.

During the COST 323 action, it emerged that more advanced research on WIM was necessary to fulfil the latest requirements of road managers and decision makers. Therefore, in 1994, the 4th Framework Programme of the European Commission was presented and a proposal for a large research project 'WAVE' (**W**eigh in motion of **A**xles and **V**ehicles for **E**urope) was submitted to the Commission by a consortium of 11 partners from 10 countries (fig. 1), following the first call in March 1995. A majority of the partners were already participants in the COST 323 action. The project began in September 1996 and lasted until June 1999.

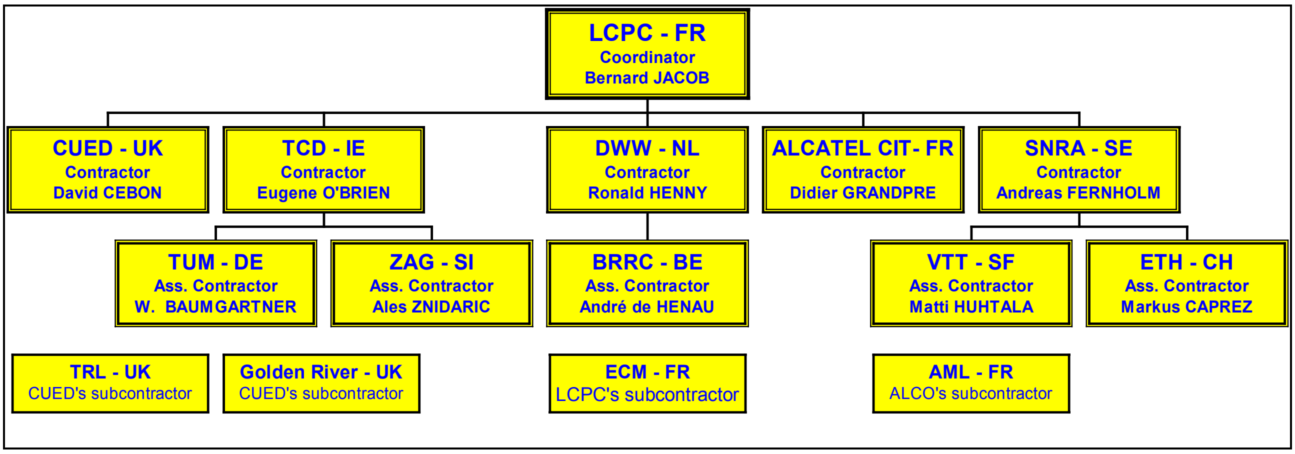


Figure 1 - WAVE consortium (1998)

1.2 Objectives

The objectives of the project were defined according to the state-of-the-art for WIM activities. Indeed, various types of WIM sensor had been developed prior to WAVE (piezoceramic cables and bars, piezoquartz bars, capacitive strips and mats, strain gauge or load cell scales, etc.) and advances in sensor and electronic technology had resulted in operational systems since the end of the 1980's. Such systems have been widely installed and operated in some countries. However, existing WIM systems still had limited accuracy and/or excessively high cost, and their durability in many circumstances was not proven. Therefore some improvements were still required.

Road surface roughness induces vibration in heavy vehicles, which results in turn in fluctuations of the dynamic tyre forces on the pavement and significantly affects the accuracy of static load estimates. A new concept of multiple-sensor WIM (MS-WIM), introduced a few years ago in the UK and FR and tested in a preliminary way by numerical simulation and road tests, was to be developed and improved in WAVE to address the issue of dynamics.

Bridge WIM systems (B-WIM) involve the use of an existing instrumented bridge as a large weighing scales for lorries which pass overhead. Initially introduced in the USA, these systems had been used on a small scale and developed in a few European countries such as IE and SI. Their particular advantage is one of durability as most of the system is underneath the bridge. If more developed and extended to various types of bridge, they can be much more widely used. While best known for applications in bridge loading and assessment studies, weight statistics collected using B-WIM systems can be used for all WIM applications.

The required data and a common background and model for future European-wide WIM databases were identified. The quality and accuracy of data depends greatly on the calibration of WIM systems and their stability in various climatic conditions. Particularly for cold climates, pavements subject to frost heave, salt, snow, ice, studded tyres and snowploughs are all contributors to a harsh environment for WIM sensors.

Some fibre optic WIM systems had already been studied. A feasibility study, carried out in France, demonstrated how the use of polarisation effects for single-mode fibres could turn a defect inherent in single-mode fibres into a prime quality for WIM sensors. Some prototypes of parts of the system had already been tested under traffic conditions prior to WAVE. Great potential exists for optic fibre WIM systems to gain information on tyre pressure and vehicle damping, much more so than with traditional WIM systems.

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

- Improve the accuracy of conventional WIM systems in their estimates of static loads from the measurements of dynamic impact forces, through the use of arrays of sensors whose results can allow for the dynamic interaction between vehicle and pavement (WP1.1).
- Develop and improve the functioning and accuracy of bridge based WIM systems through more sophisticated vehicle/bridge interaction modelling and data processing and extend bridge WIM to a wider range of bridge types (WP1.2).
- Develop common data structures, formats and quality assurance procedures, to facilitate the exchange and comparison of WIM data throughout Europe, to increase confidence in such data and to provide reliable management information to decision makers (WP2).
- Implement field tests of WIM systems, particularly in cold regions where pavements are weaker during the thaw and sensors are susceptible to studded tyres and de-icing salt, in order to assess their durability and performance in various climatic conditions (WP3.1).
- Develop standardised calibration methods and procedures by improving existing methods, applicable to all European climates and types of WIM system, to assess the reliability of WIM and facilitate relations between vendors and users (WP3.2).
- Develop and implement a new WIM technology, based on an innovative fibre optic sensor which is very promising in terms of quality and the extent of information provided and an insensitivity to harsh climatic conditions (WP4).

The different research axes were addressed in Work Packages (WP's). Each WP had a technical co-ordinator, or package leader, as described in Table 1:

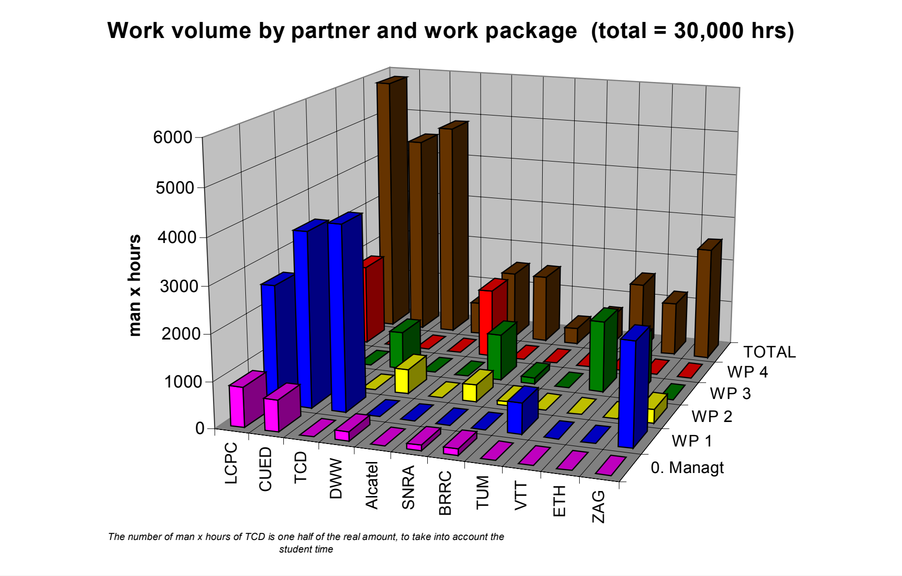
WP	Title	Leader
1.1	MS-WIM (Multiple-Sensor WIM)	D. Cebon (CUED-UK) + M. Siffert (LROP/LCPC-FR)
1.2	B-WIM (Bridge-WIM)	E.J. O'Brien (TCD/UCD-IE)
2	Quality, management and exchange of WIM data	R. Henny (DWW-NL)
3.1	Durability of WIM systems in cold climates	B. Hallström (SNRA-SE)
3.2	Calibration of WIM systems	M. Huhtala (VTT-FI)
4	FO-WIM (Fibre-Optic WIM)	J-M. Caussignac (LCPC-FR)

Table 1 - Work package leadership

1.3 Means and organisation

All together, more than 15 senior scientists and engineers, 25 Ph.D. students, post-doctoral or young engineers or researchers, and many technicians were involved in WAVE. The total time spent on the project was nearly 30,000 person-hours, i.e., 20 person-years with the breakdown shown in Figure2.

A total budget of 1.5 million Euros was allocated to this project, of which 0.75 million Euros was provided by the European Commission. Figure 3 gives the proportion of this budget for each WP and by type of cost. Workpackage WP0 represents the management of the project, as well as the publicity and dissemination activities. The personnel cost represents 69% of the total budget.



The number of man x hours of TCD is one half of the real amount, to take into account the student time

Figure 2 - Breakdown of the work volume

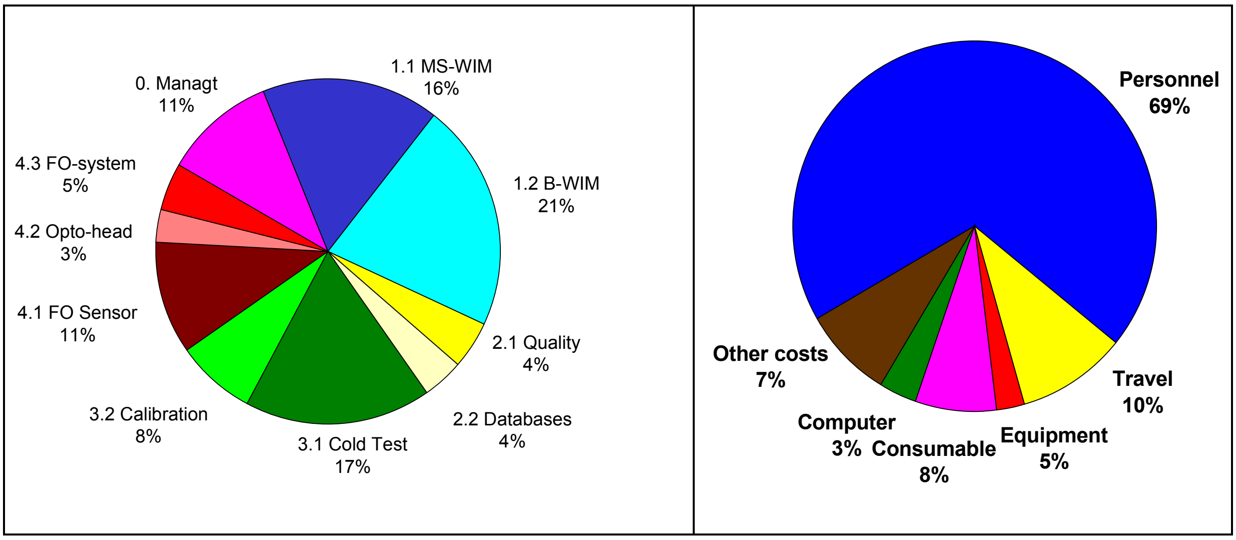


Figure 3 - WAVE budget by WP and type of cost

The project was managed by the co-ordinator and a Steering Committee consisting of the representatives of the six contractors. The Steering Committee was responsible for the general management and administration of the project, budget supervision, legal aspects, IPR management, publicity of the project and the relationships with the EC executives. A Scientific and Technical Committee was responsible for the scientific and technical management of the project. The Partner Assembly consisted of the representatives of the contractors and associate contractors; it was the main structure for the exchange of information on the project results and schedule, and ensured strong links between the different partners and packages. It held 8 plenary meetings through the period of the project.

Several large testing facilities or bridge and road test sites were used in WAVE. Two road sections were instrumented with multiple-sensor arrays, for testing MS-WIM systems. For the calibration of these arrays, instrumented lorries and pre-weighed lorries were used. Several bridges of different type were instrumented.

2. TECHNICAL WORK, IMPLEMENTATION AND DISSEMINATION

2.1 Improved accuracy of WIM systems for new applications (WP 1.1 and 3.2)

A fundamental limitation in the performance of WIM systems is imposed by the dynamic tyre forces due to vehicle-pavement interaction. The aim of WP1.1 was to develop new procedures for Multiple-Sensor Weigh-in-Motion (MS-WIM) in order to improve the accuracy of weight estimates. Since cost is also an important issue for future implementation of MS-WIM systems, it is necessary to search for a design which balanced the requirements of accuracy with the number of sensors needed.

Two theoretical studies were undertaken on MS-WIM: one in the UK (CUED) and one in France (LCPC). The work involved the development of analysis methods and algorithms for processing the outputs of MS–WIM sensors; as well as simulation studies to test the methods. Two new methods for estimating the static weight from WIM measurements were developed:

(i) the first approach, developed by LCPC, is a deterministic one. It is based on a simplified modelling of heavy vehicles and uses mathematical signal processing tools for a signal reconstruction (SR);

(ii) the second approach, developed by CUED, is a probabilistic approach. It is based on a Maximum Likelihood (ML) estimation. It fits one or two sine waves to the measured dynamic tyre forces to produce an unbiased estimate of the mean value.

Experimentation was carried out on different MS-WIM arrays: Metz and Trappes (FR) and Abingdon (UK). Both approaches were implemented and compared to the sample mean (SM) method. With simulated or theoretical impact forces, the SR method was proven to be very accurate and to give a gross weight estimation within ± 2% of the static weights. Under the same conditions, the ML method with two sine waves also gave a much better accuracy than the SM method. However, because of the sensor noise and some difficulties in the field tests with the site data, the accuracy of each method for experimental data was similar. Therefore, the main conclusions are that the newly developed algorithms are unproven for great increases in accuracy but promising and that the individual sensor performance should be increased.

Any WIM system must be calibrated before being used, and recalibrated at periodic intervals, in order to remove bias. However, calibration results are sensitive to external parameters (climate, road conditions, traffic conditions, etc.). Moreover the calibration cannot be done according to any metrological requirement, because there is no metrological definition of an axle/wheel weight; that is not a traceable quantity, because the measurement cannot be checked using standard masses. The factors affecting the accuracy of a WIM system are outlined in the WAVE report. Using an instrumented vehicle as a calibration tool and linking in with an analysis of the experimentation, a procedure for calibration by axle rank was proposed. An extensive analysis of the existing calibration methods for each type of WIM sensor was also conducted.

The main findings of WP3.1 were:

(i) a WIM system should be periodically recalibrated, especially after any system modification or change in the road or traffic conditions; if the on-site temperature range is great, calibration checks are required during each season;

(ii) fully loaded and half-loaded lorries, equipped with air suspension, are mainly recommended for calibration;

(iii) the old VTT instrumented vehicle did not provide sufficiently accurate results for calibration, and the cost of a vehicle instrumentation and dynamic calibration is rather high, but perhaps not excessively so if the vehicle is used for a range of applications;

(iv) calibration by axle rank provided promising results. Systematic biases were found for many WIM systems at various sites These biases depend on the axle rank, and were partially explained by the dynamics of the vehicles and the sensor behaviour. A calibration by axle rank can remove or reduce these biases, and thus improve the WIM accuracy for static weights and loads estimation.

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2.2 Improving durability of WIM systems in cold climates (WP 3.1)

The objective was to test the capability of existing and future WIM systems to operate effectively in cold and mountainous climates under harsh conditions, and to evaluate their performance and durability in such conditions. The main test (CET: Cold Environment Test) was carried out in northern Sweden (Luleå), while additional tests were organised in the Swiss Alps on the St Gotthard and San Bernardino roads. The CET lasted a full year, from June 1997 until June 1998. Three marketed systems (bending plate by PAT, piezoquarz sensors by Kistler and Golden River -KI/GR-, piezoceramic nude cables by Datainstrument -DI-) and one prototype (large instrumented structure by Omni Weight Control -OWC-) were tested, as well as one bridge WIM system.

All WIM systems survived over the winter. The OWC system missed or wrongly identified a large proportion of the vehicles as the system had no position sensor. The PAT system had a large proportion of outliers in the data, because of vehicles passing partially outside the relatively narrow weighing pads. The KI/GR combined system was quite stable throughout the year and provided the best results in accuracy class C(15) for the whole year. The accuracy of the PAT system, which was sensitive to the temperature, varied between C(15) and E(30) depending on the season. The manufacturer developed a temperature compensation after the test. Month after month, the accuracy of the DI system fell from E(45) to E(65). The automatic self-calibration was highly affected by the trucks passing partially outside the traffic lane. The OWC prototype was improved at the end of the test by modifications of the software, and its accuracy jumped from E(70) to E(30). The B-WIM system accuracy was found initially to be in class C(15) and later, after adjustment of the data acquisition system, in class B(10).

In Switzerland, two capacitive strip sensor systems by Golden River were installed in June 1995 at the Gotthard site, at 1100 m above sea level (one in each direction). At the San Bernardino site, 660 m above sea level, two bending plate systems by PAT were installed (one in each direction). In 1996, the Golden River capacitive sensors failed. In 1998, they were replaced with piezoquartz sensors by Kistler. The PAT system was in class C(15), and class B(10) was mostly met in the northern direction. The Golden River system was in class C(15) in one direction and in class E(30) in the opposite direction. The Kistler/GR combined system was in class C(15) in one direction and D+(20) in the opposite one.

2.3 New technologies (WP 1.2 and WP 4)

Two new WIM technologies were developed: Bridge-WIM systems (WP1.2) and optical fibre sensors (WP4).

B-WIM algorithms were improved in order to increase the accuracy of results, and also to extend their applicability to other types of bridge, e.g. short slabs, box culverts, integral construction, long span bridges, including box girders and orthotropic decks. A new approach was developed for orthotropic steel deck bridges with a system that required no axle detector on the road surface. Subsequently, this concept of "FAD" (Free of Axle Detector) B-WIM systems was extended to other types of bridge. As the whole length of the span is used for weighing, B-WIM systems should provide accurate results, but there are potential problems with selection of the structure and its influence line, measurement of vehicle velocity, vehicle-bridge dynamics and calibration. These problems were shown to be readily surmountable and high accuracy was achieved in B-WIM systems with outstanding durability. Further, great progress was made with the development of automatic calibration procedures that required no knowledge of the structural behaviour of the bridge.

The dynamics of the lorry crossing event was addressed using finite element methods, validated by on-site tests on the Belleville composite bridge (FR). A FAD optimisation algorithm was developed in which the velocity, number of axles and axle spacing are all determined from the strain gauges underneath an orthotropic deck bridge, and it was validated on the Autreville bridge (FR). Then, this algorithm was extended and adapted to other types of bridge and implemented in Slovenia. A new WIM program, SiWIM© was developed by ZAG for use with any type of bridge and which can be used with a range of alternative weight calculation algorithms. Its main tasks are: data acquisition, filtering and monitoring, vehicle detection and weight calculation, in real time or off-line.

Another theoretical approach to B-WIM was to use multiple sensor locations longitudinally on the bridge, modelled using a static algorithm. There are generally more equations relating strains to axle weights than unknown axle weights, so the best-fit solution is chosen. However, the resulting equations are not always independent. A preliminary experimental verification was carried out on the Belleville bridge. The multiple equation system was shown to be more accurate (by one to two accuracy classes) than the conventional B-WIM system.

A combined Bridge and Pavement WIM system, which uses additional information obtained from the pavement sensors in the form of estimates of instantaneous dynamic axle weights, is quite insensitive to minor errors in the input data. The algorithm was theoretically examined by generating simulated dynamic axle forces for the pavement system and bending moment influence responses for the B-WIM system. Theoretical testing showed that the combined algorithm could reach class B+(7) when systems individually gave class B(10).

Alternative algorithms based on modelling the dynamic behaviour of the bridge-truck system were developed, using a spectral approach and a *dynamic multiple-sensor algorithm.* This method is based on the accurate determination of the theoretical strain response due to a moving constant load at different bridge locations. The dynamic adjustment is much closer to the measured strain than the static adjustment. A dynamic bridge WIM algorithm (DB-WIM) based on one sensor location was also developed. The difference from the conventional approach is the use of the dynamic response due to a unit load instead of the influence line. Taking into account the influence of dynamics is interesting but is most relevant for medium to long-span bridges, about 10% of the bridge stock.

Several tests were carried out in France, Slovenia, Sweden and Germany on various types of bridge. The accuracy was generally between C(15) and B(10) when the newly developed algorithms were used.

The feasibility of using single mode optical fibre as the sensitive element for sensing and the interferometry principle was assessed by LCPC and Alcatel in the early 1990's. The next steps were to design a suitable WIM strip sensor and to develop the adapted optoelectronic system. A new sensor design was made after testing a lot of prototypes. Numerous laboratory tests were performed to assess its performance. The optoelectronic head was also developed, as well as the required software, and the device was designed to allow it to be inserted into an MS-WIM optical fibre system. In fact, the design of MS-WIM is consistent with the ease with which optic fibres can be multiplexed. For this, technologies were transferred from techniques applied to communication optical links. Laboratory tests showed that quality improvement between the first and last generation of sensors allowed the best spatial homogeneity of the sensor response to be found. A prototype system with two parallel 3.7 m optical sensors and a 1.5 m sensor was tested on a parking lot in Saintes (FR) by November 1998. This experiment was also used to test the acquisition system and to develop the processing software. The resolution of 30N, independent on the load, corresponds to a quarter of a fringe. Such a resolution is obtained thanks to an extreme sensor sensitivity and a suitable signal processing. Now, for a car wheel, the absolute error is ± 300N, a very low value. Combining the static weight error and the absolute error on site, a fairly good relative accuracy for heavy wheels and axles can be expected. For these loads, the accuracy becomes better than 5 %. The chosen mean loads were similar to a force induced by a heavy truck wheel.

Optical fibre WIM sensors provide a good metrological accuracy and a low temperature dependency. Furthermore, optical WIM systems can operate both statically and at high speed. It also has an electromagnetic immunity, that means that sensors and cables may be laid near high voltage wires and live railway tracks. The system is as easy to install as any other WIM strip sensor system. Moreover, electric power is not necessary along the roadway and the distance between the sensors and the optoelectronic head can reach up to 2 km. Data processing can be performed in real time. Finally, optical fibre systems are a well-suited method to be connected with an optical bus and with a network.

The signal processing methods are still being developed. That will allow more information to be provided as a result of a greater wealth of information in the signal, such as: tyre pressure and width, vehicle accelerations and dynamics, suspension characteristics, etc..

2.4 Data management and quality (WP 2 and general input from all packages)

An increasing demand for WIM data in Europe makes the exchangeability of these data between different countries and systems an important issue. Thus, a very important issue was to transform the available data into a common European format. Due to the various measuring methods and site characteristics, there was a need for quality indices to qualify and classify the submitted WIM data. A whole Quality Assurance (QA-) system was developed; the background and the procedures enable the European WIM database and QA system to be implemented after the conclusion of the project, as soon as decisions are taken by the users and decision makers.

The aim of the QA-system is to provide the user with information on the quality of the stored data. Therefore, there are different issues such as evaluating the consistency of the information (coherence tests), or the accuracy of the measurements. Quality parameters were proposed as indicators based on information about the weighing equipment, the pavement conditions and other parameters. The input from site and the environment, such as climate, road curvature, transverse slope, longitudinal slope and distance to last junction, type of pavement, deflection, longitudinal evenness, and transverse evenness, to the quality of WIM information is considered.

As there is currently no scientific basis on which to quantify these quality parameters, an alternative procedure is proposed as an interim measure which uses the opinion of experts. The European database of WIM contains two main levels: site data and statistical traffic load data. Logical coherence tests or comparisons of statistics (mean, standard deviation, etc.) to reference values are performed. Ageing factors were introduced to account for the pavement and the sensor deterioration, while no recalibration is performed.

2.5 Implementation and dissemination

The COST 323 action facilitated the dissemination of the WAVE results through the organisation of the Second European Conference on WIM (COST323, 1998). The WAVE consortium organised two European seminars to keep national authorities and the WIM industry informed of results from the project: a mid-term seminar in Delft (WAVE, 1997) and a larger final symposium in Paris, with more than one hundred participants. This provided the audience with the final conclusions and results from the project. It was well attended by road authorities, WIM manufacturers and decision makers from a great number of European countries. The proceedings were published in the form of a book (Jacob, 1999) by an international publisher. The results and output of WAVE were also presented at other International conferences, such as the Transport Research Board Annual Meeting in January 1998, NATMEC'1998 (North American Traffic Monitoring Exhibition and Conference), the 5th International Symposium on Heavy Vehicle Weights and Dimensions (Brisbane, Australia, April 1998), the 2nd ERRC (European Road Research Conference), (Jacob and O'Brien, 1999), and in the Vehicle/Infrastructure Interaction conference in Poland in September 1999. A WIM session was held at the 21st World Road Conference organised by PIARC in Kuala-Lumpur (September 1999), in which WAVE was presented. A WIM seminar was organised in Taiwan in April 1999, with a significant participation of the WAVE partners. Additional results will be presented in the 3rd ICWIM (International Conference on WIM, Orlando, Florida, May 2002).

Most of the existing and developing WIM technologies were implemented as prototypes or in full scale tests, throughout several countries. Most of the manufacturers gained experience from the tests while the customers and users became more confident in the marketed products. The European database with its quality assurance (QA) system provides a framework and tools for road and infrastructure managers, and for road transport authorities, to get easy access to an overview of the WIM system network and heavy vehicle traffic in Europe. However, the implementation and dissemination of such a database will require long-term support, and some maintenance. A proposal was made to the WERD (Western European Road Directors) and to the FEHRL in 1999, to organise and support this action. The subject was discussed at a few meetings, but until now no common decision was taken. Without any decision and allocated means, there is a risk of losing the benefit of the work completed in WP2 of WAVE.

The concept of MS-WIM was enhanced in the project. Two new algorithms became available as deliverables of the project. Two manufacturers were directly involved in the implementation of MS-WIM arrays. A request was expressed in several EU countries to implement MS-WIM systems for enforcement of overloaded vehicles. That is one of the major challenges of the coming years, as static controls become less and less efficient with increases in heavy vehicle traffic and budget and staff restrictions. The dissemination of this technology will depend on the individual accuracy of the sensors, which is now a limitation for legal application, on the type approval of such an approach by the Legal Metrology authorities, and of course on the market price of the systems.

The project transformed B-WIM from an early stage of development into a mainstream WIM technology at a level comparable with all others. A number of major sources of inaccuracy were identified and addressed. Computer models were developed and validated to simulate the process and algorithms developed which take account of dynamics in their calculation of static axle weights. Optimisation methods were applied to increase the algorithm efficiency. Full scale field tests assessed the good accuracy of typical B-WIM systems. The range of bridge types that are suitable for B-WIM was extended considerably and the durability of the systems was substantially improved with the development of Free of Axle Detector (FAD) B-WIM systems. The SiWIM© software is in the process of full commercialisation and its open architecture will be of great benefit for other developers.

The fibre optic (FO-)WIM system was greatly developed, even if some delay occurred because of a major change of partner within the Alcatel group. The sensor design was formalised and successfully tested. The whole opto-electronic unit and software was completed and validated. The system was also designed to be capable of managing MS-WIM by multiplexing several sensors. However, because of the above mentioned delay, it was neither possible to test the whole FO-WIM system on a trafficked road under real traffic conditions, nor to implement a MS-FO-WIM system. Nevertheless these tasks will be performed after the project, within the framework of a bilateral collaborative project between LCPC and Alcatel. While all the other current research works on FO-WIM are focused on a rather simple technology (light attenuation), which is not accurate enough for WIM of class C(15) or better, the marketed systems are currently specified only for vehicle classification. The technology developed before and improved in the project, has a much more promising performance, and the prototype sensor seems to be competitive with the best existing WIM sensors. If further tests are satisfactory, this WIM system is expected to be marketed at a rather low price compared to existing high quality systems, and to provide a high value for money for the users. Moreover, additional measurements are expected with these sensors, concerning the vehicle dynamics and tyre pressure or other characteristics.

3. CONCLUSIONS

The WAVE project has been rich in theoretical and applied works, experimentation and data collection and analysis. It has given a great impetus to the technology of WIM, leading to improved accuracy and applicability.

Until now, static weighing has been the only way to detect overloads. The number of vehicles weighed is still far too small for enforcement to have a significant dissuasive effect. Furthermore, these operations are becoming more and more difficult, cumbersome and expensive. WIM seems to be an ideal means of substantially increasing the number of vehicles checked. However, such a legal application requires a higher accuracy in static weight estimation and a means of dealing with the dynamic interaction between vehicles and infrastructure. That was the main objective of multiple-sensor (MS-)WIM, which now becomes a credible way of implementing automatic controls at high speed. Even if the MS-WIM precision must still be improved to allow direct enforcement use by inspection departments, they can already be used to screen traffic for overloaded vehicles that can then be intercepted and weighed statically, or at low speed.

The fibre optic sensors provided encouraging preliminary results, with a design well adapted to accurate weighing. The feasibility of a whole FO-WIM system was proven. The marketing of this technology is expected in the near future, and much progress was achieved in WAVE. However, the manufacturer still has to complete further R&D work to implement operational software, to successfully pass a long-term performance test on a trafficked road, and then to market the new product.

The WAVE project placed great emphasis on the study of weigh in motion using instrumented bridges (B-WIM), and the results obtained are highly encouraging. This system is relatively inexpensive and can now be implemented on a great range of bridge types, particularly at strategic points on the road network. Further, the portability of these systems makes it possible to move them from time to time to overcome the difficulties that result from drivers becoming aware of their location. Currently, the precision attained is easily comparable to that of road sensor WIM systems. These systems can be installed without interrupting traffic. The Free of Axle Detection (FAD) type is not detectable; they are largely tamper-proof and difficult to avoid simply by swerving or changing lanes. They are therefore of great value for the monitoring of road transport. Another valuable application of B-WIM is for bridge monitoring, rehabilitation or assessment. A B-WIM system may provide synchronised data on the traffic load effects and the induced stresses and strains. This greatly helps to understand the real behaviour of the monitored structure and to assess its structural safety with respect to the expected traffic. B-WIM systems could therefore become a part of "Intelligent Bridge Monitoring Systems" to optimise greatly the allocation of funds for bridge repairs or replacements and to reduce the corresponding traffic disturbance.

The tests carried out in Sweden and Switzerland in a cold environment revealed the performance and weakness of each sensor or system, depending on the time of year, the calibration procedure, and other factors such as the traffic conditions. The increase in experience and knowledge was of great benefit, both for the manufacturers and the users.

The calibration methods proposed in the European Specifications on WIM (COST323) were investigated in detail and tested at different sites and with all types of WIM sensor. It was shown that MS-WIM arrays should be calibrated with the true impact forces sensor by sensor, and not with the static weights. That may be achieved either using an accurately instrumented lorry, or at very low speed using the static weight and neglecting the dynamic effects. The first method requires expensive and rare vehicles, while the second method only applies for some types of sensor which perform identically at low and high speeds. It was also shown that some inter-axle load transfers occur while the vehicles are travelling at speed, which may disturb the calibration of WIM systems. Therefore, a calibration "by axle rank" was proposed and tested with a few samples of lorries and on two WIM sites. This method may slightly improve the accuracy of a WIM system.

An original Quality Assurance system of WIM data was designed. It takes into account the site and environmental conditions, some expert (prior) knowledge on each type of sensor behaviour, but above all the dates and results of calibration or checking sessions. Then a rating is allocated to the collected data for a year, and this rating automatically decreases with time if the system is not maintained (recalibrated), or if no information is provided for a number of years. With such a system, the users and decision makers have a measure of what confidence they may have in the data stored in the European database of WIM.

The conditions of international co-operation on Weigh-in-motion of road vehicles were exemplary, since, at first through a COST project and subsequently through a European RTD project, a large number of European countries have taken part in this work. This work is being followed with keen interest on the other continents, particularly in North America.

The advances made possible by WAVE open up the prospect of a transition to full-scale use and therefore to commercial distribution of the new WIM devices. The participation of the manufacturers in such a step is fundamental, and their contributions to the project were highly valuable.

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