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Weigh-in-motion of
Axles and
Vehicles for
Europe

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

General Report

Laboratoire Central des Ponts et Chaussées *April 2001*

Organisations and participants

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	G. de Vaulchier → D. Grandpré	ALCO → Alcatel Saintes	France
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	S. Jehaes	Belgian Road Research Centre	Belgium
	W. Baumgärtner	Technische Universität Munchen	Germany
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	M. Caprez	Swiss Federal Institute of Technology	Switzerland

ABSTRACT

Weigh-in-motion (WIM) of Road Vehicles is essential for the management of freight traffic, road infrastructure design and maintenance and the monitoring of vehicle and axle loads, in the context of harmonised European legislation. A considerable demand has emerged in recent years for more accurate and reliable WIM systems and sensors, in order to provide road authorities and managers with up to date and on-line measurements of axle and vehicle weights. New technologies were proposed in the last decade, which needed either to be developed or improved.

During the COST 323 action (WIM-LOAD), a shared-cost action of COST Transport (1993-98), it emerged that more advanced research on WIM was necessary to satisfy the latest requirements of road managers and decision makers. As a result of this, a proposal for a large research project, 'WAVE' (**W**eigh in motion of **A**xles and **V**ehicles for **E**urope), was submitted in 1995 to the European Commission. It was part of the 4th Framework Programme (Transport) and was proposed by a consortium of 11 partners from 10 countries. The project began in September 1996 and lasted until June 1999.

The whole WAVE budget was € 1.5 million, of which € 0.75 million was provided by the European Commission. The project was co-ordinated by the Laboratoire Central des Ponts et Chaussées (France), and the contractors were: Cambridge University - Engineering Department (UK), Trinity College Dublin (IE), Rijkwaterstraat (NL), Alcatel CIT (FR), Swedish National Road Administration (SE). The associate contractors were: Belgium Road Research Centre (BE), Technical University of Munich (DE), Technical Research Centre of Finland (FI), National Building and Civil Engineering Institute of Slovenia (SI), Swiss Federal Institute of Technology (CH).

The objectives and Work Package organisation of the project were:

- 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 period 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 procedures by improving existing methods, applicable to all European climates and types of WIM system, of assessing 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 has considerable potential in terms of quality and the extent of information provided and an insensitivity to harsh climatic conditions (WP4).

The main outputs of the project were:

- Two new algorithms for Multiple-Sensor Weigh-in-Motion (MS-WIM), a deterministic one based on a signal reconstruction, and a probabilistic approach based on Maximum Likelihood Estimation, were developed. The theoretical accuracy of these methods, assessed using simulated or theoretical impact forces, were shown to be higher than a simple averaging of the individual sensor readings. However, the research was affected by the limited amount of data available and some difficulties encountered in the experimentation carried out in France and the UK. This led to the conclusion that these algorithms are unproven but show promise for substantial increases in accuracy relative to the simple averaging method, and that the individual sensor performance should be increased. MS-WIM is expected to be used for legal application and overload enforcement in a near future.
- Bridge (B-)WIM algorithms were improved in order to increase the accuracy and to extend their applicability to a greater range of bridge types. A new approach was developed with a system that required no axle detector on the road surface (Free of Axle Detector, FAD B-WIM). A good accuracy was achieved in B-WIM systems - currently, the precision attained is easily comparable to that of road sensor WIM systems -, with outstanding durability. Tests were carried out on several types of bridge and a user-friendly program interface was developed to facilitate the implementation of B-WIM, either in real time or off-line. Moreover, the combination of MS-WIM and B-WIM concepts, and modelling of the dynamic behaviour of the bridge-truck system, were proposed to improve the accuracy up to a high standard. B-WIM systems are relatively inexpensive, portable, durable and can now be implemented on a great range of bridge types. They can be installed with minimal disruption to traffic. The FAD type involves nothing on the road surface and is therefore safe to install and undetectable to road users. For bridge monitoring, B-WIM systems may provide synchronised data on the traffic load effects and the induced stresses and strains, and therefore become a part of "Intelligent Bridge Monitoring Systems" to optimise the allocation of funds for bridge repair or replacement and to reduce the corresponding traffic disruption.
- A single mode optical fibre was used as the basis for a new WIM sensor. An optoelectronic system was developed for the new sensor which is also capable of managing a MS-WIM optical fibre system. Laboratory tests were performed to assess its performance and a prototype system was tested in a parking lot. The system can operate both statically and at high speed, with a resolution of 30N, independent of the load, and a low temperature dependency. It also has an electromagnetic immunity, that means that sensors and cables may be laid near high voltage wires and live railway tracks. 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. 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 rela-

tive accuracy for heavy wheels and axles can be expected. The fibre optic sensors provided encouraging results, and it is anticipated that this technology will be commercially exploited. As a result of a greater wealth of information in the signal, it is expected that more information will be provided in the future such as: tyre pressure and width, vehicle acceleration and dynamics, suspension characteristics, etc..

- Calibration of a WIM system is a critical but major issue to ensure the accuracy of the data. However, WIM sensors are sensitive to external parameters (climate, road conditions, traffic conditions, etc.). Moreover, the calibration cannot be done according to any metrological standard or use of standard masses. The calibration methods proposed in the European Specifications on WIM (COST 323) were extensively used at different sites and with all types of sensor, and were proven to be very efficient. MS-WIM arrays should be calibrated with the true impact forces sensor by sensor, using an instrumented vehicle and not with the static weights, or at very low speed 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. 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.
- Tests of WIM systems in cold and mountainous climates under harsh conditions were carried out in northern Sweden (CET: Cold Environment Test), and on two sites in the Swiss Alps. Most of the systems encountered problems, to different extents, but all survived over the winter. The accuracy of these systems was highly dependent on the technology, and, in most cases, varied with time and with temperature. The calibration procedure and other factors such as the traffic conditions also affected the accuracy. The increase in experience and knowledge was of great benefit, both for the manufacturers and the users.
- An original Quality Assurance system of WIM data was designed. The background and the procedures make it feasible for a 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 QA system takes into account the site and environmental conditions, some expert (prior) knowledge on the behaviour of each type of sensor, 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 WIM database.

The results and output of WAVE were presented at a Final Symposium in Paris in May 1999 to more than one hundred participants and the proceedings were published in the form of a book. Many papers were also published in conferences and journals.

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

Acknowledgement
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1. GENERAL OBJECTIVES OF WAVE

1.1 Needs and Requirements for Weigh-In-Motion (WIM)

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 has 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. For building, operating and maintaining new infrastructure under concession contracts, it becomes necessary to get accurate data about real traffic loads and volumes.

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.

The development of WIM for the estimation of axle and vehicle weights as lorries travel at speed has been ongoing for the last 20 years, especially in Europe (Jacob, 1996). Some countries developed WIM systems in the 1970's and 1980's, such as France and the United Kingdom, and have been using them for two decades, while others developed WIM networks more recently (e.g., Portugal, Hungary). Many more counties have investigated the possibility of using WIM systems or have installed a small number. In the late 1980's and early 1990's, a great demand arose for improved WIM technology, more durable and accurate sensors, more powerful electronics, and for specifications to facilitate the commissioning of such systems. Later, quality assurance of WIM data emerged as a growing need. European countries and the European Commission itself supported these needs, but experience in the field was restricted to a number of isolated pockets. There was a clear requirement for co-operative action and further advanced research, in order to fulfil the latest requirements of both road managers and decision makers. Therefore, 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 between member countries.

The COST 323 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.

1.2 Origin of the Project

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. In 1994, the 4th Framework Programme of the European Commission was presented, with a specific "Road Transport programme", a part on "Road infrastructures" and a task entitled "Monitoring of factors affecting pavements and structures to support existing and future harmonisation legislation in respect of axle and vehicle weights" (task 7-4/27).

Therefore a proposal for a large research project 'WAVE' (**W**eigh in motion of **A**xles and **V**ehicles for **E**urope) was submitted to the Commission by a consortium of 11 partners from 10 countries, following the first call in March 1995. A majority of the partners were already participants in the COST 323 action. After a positive review by the experts and a negotiation phase in Autumn 1995, the project began in September 1996, after a 6 month delay due to the negotiation of a general agreement between the Commission and the PECO countries (Eastern European Countries) in order to allow them to be funded for such research projects. It is the objective of this project to provide a significant step forward in the understanding and further development of WIM with respect to road networks for managers and decision makers (Jacob 1996; Jacob and O'Brien 1996).

1.3 Project Baseline

Various types of WIM sensor have 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 have resulted in operational systems since the end of the 1980's (Jacob, 1999a). Such systems have been widely installed and operated in some countries (COST323, 1997). 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 (Jacob, 1995). A new concept of multiple-sensor WIM (MS-WIM), introduced a few years ago in the UK (Cebon, 1990) and France, and tested in a preliminary way by numerical simulation and road tests, was to be developed and improved in WAVE, which may solve this issue.

Bridge WIM systems (B-WIM) involve the use of an existing instrumented bridge as a large weighing scales for lorries which pass overhead (Žnidarič and Baumgärtner, 1998). Initially introduced in the USA, these systems have been used on a small scale and already further 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 generalised 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 report on WIM needs and requirements in Europe (COST 323, 1997) was considered and compared to existing national or other documents, to identify the required data and to provide a common background and model for future European-wide WIM databases (Siffert et al., 1998). The quality and accuracy of data depends greatly on the calibration of WIM systems and their stability in various climatic conditions. Cold climates, frost pavements, salt, snow, ice, studded tyres and snowploughs are all contributors to a harsh environment for WIM sensors. Previous experience was taken into account and built upon.

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 to single-mode fibres into a prime quality for WIM sensors (Teral and Caussignac, 1995). 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.

1.4 Project Objectives

The objective of the 'WAVE' project is 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.
- 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.
- 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.
- Test 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.
- 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.
- 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.

The accuracy of load measurements with respect to the harmonised legislation on axle and vehicle weights and to infrastructure damage calculations is a critical issue, not only because of the system accuracy itself, but because of dynamic effects due to the pavement roughness and vehicle suspension 'bounce'. The calibration of WIM systems is also a difficult issue and depends highly on the application and environment.

The quality and control of the data, the storage and processing tools, and the harmonisation of data collection policy are keys in facilitating a comprehensive European traffic survey for economic, technical or legal issues. It is also required that WIM systems be operated with reliability across all of Europe and hence within a wide range of temperature and in harsh climates. The behaviour of sensors and stations in cold climates, encountered half of the year in northern Europe and in mountainous regions, is crucial because of the weakness of the pavement during periods of thaw.

This project constituted a strategic policy initiative to confirm the leadership of Europe in WIM (Jacob, 1999c). It led to the development of new technologies such as advanced multiple sensor and bridge WIM systems, a quality assurance procedure to be implemented in a pan-European database (Siffert et al., 1998), a gathering of information about the behaviour of WIM systems in cold environments, an improvement in calibration procedures and the development of a new European WIM technology based on light polarisation analysis in single-mode fibres. High-performance and harmonised tools for road and transport decision makers were also provided.

2. PROJECT ORGANISATION, MEANS AND SCHEDULE, AND LINKS WITH OTHER PROJECTS

2.1 Consortium, management and schedule

2.1.1 Consortium

The initial COST 323 participants who decided to form the consortium and to prepare the project proposal in 1994 were: LCPC (France), TCD (Ireland), DWW (The Netherlands), BRRC (Belgium), SNRA (Sweden), VTT (Finland), ETH (Switzerland) and ZAG (Slovenia). Most of them (LCPC, DWW, BRRC, VTT, ZAG) are members of the FEHRL (Forum of European Highway Research Laboratories). In the UK and Germany, the COST 323 representatives, also members of the FEHRL (TRL and BaST), suggested the appointment of some universities where research teams were specialised in WIM activities. Therefore, CUED and TUM were contacted in the UK and Germany respectively, and they agreed to take part in the project. Finally, it was proposed to involve Alcatel, a multinational company with headquarters based in France, in order to cover the development of fibre optic WIM systems, because they were already experienced in this activity and a partner of the LCPC in former WIM projects (Jacob, 1996).

In order to facilitate the project organisation and to reduce the number of contracts to be signed by the Commission, it was decided to set up the consortium with 6 Contractors and 5 Associate Contractors, as follows:

Contractors :

1. Laboratoire Central des Ponts et Chaussées - LCPC - (FR), as coordinator,
2. Cambridge University Engineering Department - CUED - (UK),
3. Trinity College Dublin - TCD - (IE),
4. Road and Hydraulic Engineering Division - DWW - (NL),
5. Alcatel Contracting - ALCO - (FR),
6. Swedish National Road Administration - SNRA - (SE);

Associate Contractors :

7. Belgium Road Research Centre - BRRC - (BE),
8. Technische Universitaet Muenchen - TUM - (DE),
9. Technical Research Centre of Finland - VTT - (SF??),
10. Swiss Federal Institute of Technology - ETH - (CH),
11. National Building and Civil Engineering Institute - ZAG - (SI)

Four sub-contractors were also listed at the beginning of the project:

- Transport Research Laboratory - TRL - (UK),
- Golden River Ltd. - GR - (UK),
- Electronique Contrôle Mesures - ECM - (FR),
- Applications Mathématiques et Logiciel - AML - (FR).

TRL was appointed to supply instrumented lorries in order to perform experiments and calibration of a multiple sensor WIM system in the UK. GR and ECM, both manufacturers of WIM sensors and systems, were appointed to supply multiple sensor arrays, either in the UK or France; they are therefore self-motivated and interested in the output and deliverables of the project. AML was appointed by Alcatel to perform mathematical studies and to develop software related to the fibre optic WIM system.

Each contractor signed the same contract with the European Commission, and made a similar contract with each of its associate contractor(s). For payments, the Commission transferred the money to the coordinator, on the basis of the approved cost statements. Then the coordinator distributed the funds among the contractors, who transferred the due amounts to their associate contractors.

A consortium agreement was signed at the beginning of the project by all the partners (contractors and associate contractors), which describes the rights and obligations, the IPR (Intellectual Property Right) rules, and some related questions.

The project was planned for 24 months, from September 1996. A 9 month extension was then accepted by the Commission (DGVII), which lead to a project end in June 1999.

A modification occurred in the consortium in late May 1998, when Alcatel CIT (Saintes, FR) replaced Alcatel Contracting (ALCO). Both are sub-companies of the Alcatel Group. Alcatel CIT took exactly the same rights and obligations as ALCO, and a new contract was signed with the Commission on the same basis. However, because of some delay in the work performed by ALCO, the tasks and budget of Alcatel CIT were reduced by approximately 30% with respect to the initial plans; the remaining funds were reallocated to the other partners for programme extensions in agreement with the Commission (see § 2.3). The final consortium is presented in Figure 1.

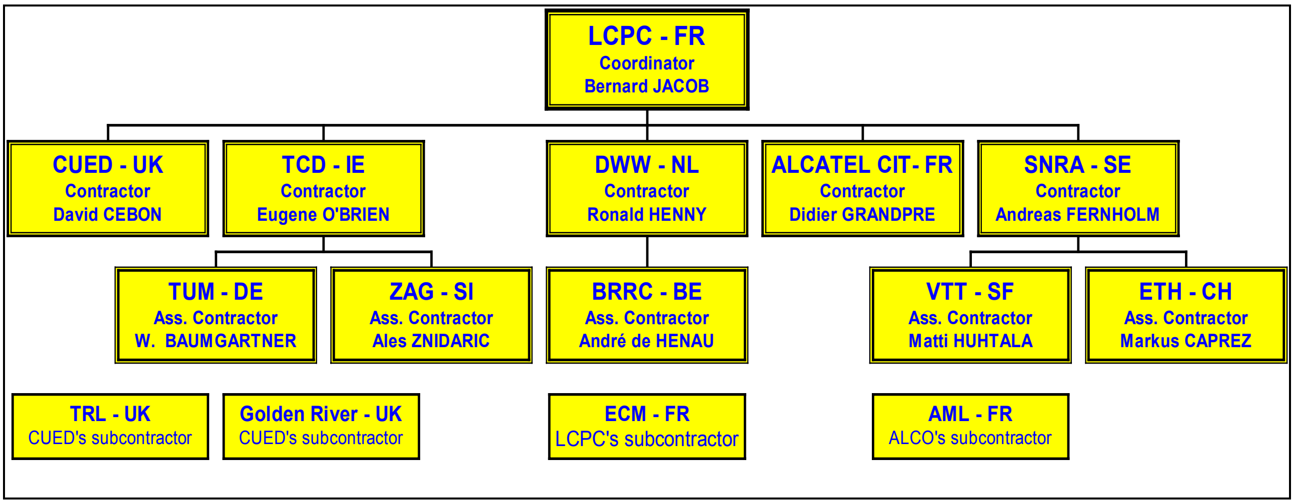


Figure 1: WAVE consortium (1998)

2.1.2 Project management and schedule

The coordination of the project was done by the LCPC (FR), and the project coordinator was Bernard JACOB (Chief Engineer of Bridges and Roads). An assistant manager helped the co-ordinator with administrative and financial issues, the management of the documents, etc..

Each work package (WP, see § 2.2) had a technical coordinator, or package leader, as described in Table 1:

WP	title	Leader
1.1	MS-WIM	D. Cebon (CUED) + M. Siffert (LROP/LCPC)
1.2	B-WIM	E.J. O'Brien (TCD)
2	Quality, management and exchange of WIM data	R. Henny (DWW)
3.1	Durability of WIM systems in cold climates	B. Hallström (SNRA)
3.2	Calibration of WIM systems	M. Huhtala (VTT)
4	FO-WIM	J-M. Caussignac (LCPC)

Table 1 : Work package leadership

Two committees took responsibility for the different tasks of the project :

- **Steering Committee (SC)**: consisting of the representatives of the six full partners, it was responsible for the general management and administration of the project, budget supervision, legal aspects and especially the issues of securing patents or granting licences, IPR management, publicity of the project and the relationships with EU/DGVII executives.

- **Scientific and Technical Committee (STC)**: consisting of the technical coordinators (WP leaders) and the project coordinator, it was responsible for the scientific and technical management of the project. It was in charge of the execution of the work packages, the identification of project milestones, the evaluation of the deliverables, the production and dispatching of progress reports and final reports. It was also responsible for the mid-term seminar and final symposium organisation, and for the dissemination of the results.

- **Partner Assembly (PA)**: consisting of the representatives of the full and associate partners and the technical coordinators, it was the main structure for the exchange of information on the project results and schedule, and to ensure strong links between the different partners and packages.

The memberships of these committees are described in Tables 2 to 4. A list of the committee meetings is given in Table 5. The SC and STC meetings were mainly held during the PA meetings. Many WP meetings were organised, either alone or in conjunction with the PA meetings.

Steering Committee		
Name	**Organisation**	**Status**
Bernard JACOB	LCPC, Laboratoire Central des Ponts et Chaussées	*Chairman*
David CEBON	CUED, University of Cambridge	*Member*
Eugene O'BRIEN	TCD, Trinity College Dublin (currently University College Dublin)	*Member*
Ronald HENNY	DWW, Directorate General for Public Works and Water Management	*Member*
Jean-Guy de VAULCHIER Didier GRANDPRE	ALCO, Alcatel Contracting *(until May 31st, 1998)* Alcatel CIT *(since June 1st, 1998)*	*Member*
Andreas FERNHOLM	SNRA, Swedish National Road Administration	*Member*

Table 2: Steering Committee

Scientific and Technical Committee		
Name	**Organisation**	**Status**
Eugene O'BRIEN	TCD, Trinity College Dublin (currently University College Dublin)	*Chairman*
Bernard JACOB	LCPC, Laboratoire Central des Ponts et Chaussées	*Vice-Chair*
Jean-Marie CAUSSIGNAC	LCPC, Laboratoire Central des Ponts et Chaussées	*WP4 leader*
David CEBON	CUED, University of Cambridge	*WP1.1 co-leader*
Bengt HALLSTRÖM	SNRA, Swedish National Road Administration	*WP3.1 leader*
Ronald HENNY	DWW, Directorate General for Public Works and Water Management	*WP2 leader*
Matti HUHTALA	VTT, Technical Research Centre of Finland	*WP3.2 leader*
Marcel SIFFERT	LROP, Laboratoire Régional de l'Ouest Parisien	*WP1.1 co-leader*

Table 3: Scientific and Technical Committee

The plans for experiments, a brief account of the raw results and the analysis procedures were discussed within the Partner Assembly (PA). The STC was responsible for the quality of the results and analysis procedures, data, and its compliance with the objectives.

The decisions concerning the scientific and technical issues, the execution of the tasks, the reporting of the work done, the dispatching of the results, etc., were taken in the first instance by the WP leaders as far as they only concerned one WP. For the most important decisions or those which involved more than one WP, the STC decided. The WP leaders reported to the STC any issues concerning their WP.

All the decisions proposed during the Partner Assembly were taken and adopted immediately, if the members of the SC or STC (depending of the nature of the issue) that were present agreed unanimously (especially if the whole PA agreed). The minutes of all the meetings were dispatched to every partner, with a copy to the Commission.

Logo	Organisation	Names
	LCPC, Laboratoire Central des Ponts et Chaussées, FR	Bernard JACOB Jean-Marie CAUSSIGNAC, Marcel SIFFERT, Victor DOLCEMASCOLO, Daniel STANCZYK…
	CUED, Cambridge University Engineering Department, UK	David CEBON Lampros STERGIOULAS
	TCD, Trinity College Dublin, IE	Eugene O'BRIEN
	DWW, Road and Hydraulic Engineering Division, NL	Ronald HENNY
	ALCO, Alcatel Contracting, FR *Replaced by* Alcatel CIT (Saintes)	Guy DE VAULCHIER, Didier GRANDPRE, Jean-Claude ROUGIER
	SNRA, Swedish National Road Administration, SE	Andreas FERNHOLM, Bengt HALLSTRÖM
	BRRC, Belgium Road Research Centre, BE	André. DE HENAU, Sophie JEHAES
	TUM, Technische Universitaet Muenchen, DE	Werner BAUMGARTNER, Stephen LUTZENBERGER
	VTT, Technical Research Centre of Finland, FI	Matti HUHTALA, Pekka HALONEN
	ETH, Swiss Federal Institute of Technology, CH	Markus CAPREZ
	ZAG, National Building and Civil Engineering Institute, SI	Ales ZNIDARIC

Table 4: Partner Assembly

Dates	Location	Committee
12/9/1996	Metz, France	Plenary Assembly, Kick-off meeting
9/12/1996	Paris, France	Plenary Assembly, 2nd meeting
7/3/1997	Cambridge, UK	Scientific and Technical Committee
6/7/1997	Luleå, Sweden	Plenary Assembly, 3rd meeting
16/9/1997	Delft, The Netherlands	**Mid-Term Seminar**
20-21/10/1997	Münich, Germany	Plenary Assembly, 4th meeting
2-3/3/1998	Paris, France	Plenary Assembly, 5th meeting
5-6/6/1998	Dublin, Ireland	Plenary Assembly, 6th meeting
3-4/12/1998	Paris, France	Plenary Assembly, 7th meeting
11-12/3/1999	Maribor, Slovenia	Plenary Assembly, 8th meeting
6-7/5/1999	Paris, France	**Final Symposium**

Table 5: Committee meetings and events

Period	Sub-period	initial dates	revised dates
I	1	9/96 - 30/11/96	9/96 - 30/11/96
	2	1/12/96 - 28/2/97	1/12/96 - 28/2/97
II	3	1/3/97 - 31/5/97	1/3/97 - 31/5/97
	4	1/6/97 - 31/8/97	1/6/97 - 31/8/97
III	5	1/9/97 - 30/11/97	1/9/97 - 31/12/97
	6	1/12/97 - 28/2/98	1/1/98 - 31/5/98
IV	7	1/3/98 - 31/5/98	1/6/98 - 31/10/98
	8	1/6/98 - 1/9/98	1/11/98 - 30/5/99

Table 6: Periods for intermediate IQCS (Internal Quarterly Cost Statement), CS (Cost Statement) and progress reports

Every three months, short progress reports were provided by the technical coordinators (WP leaders) to the project coordinator. They comprised : the financial status of the resources used in each WP, a statement of progress towards completion of each WP and the problems encountered or proposed changes to the project plans. These reports were presented to the PA and SC to compare actual progress and use of resources against planned progress and budget. The technical documents completed during the three months period were transmitted to the project coordinator and to the STC. An overall progress report was prepared by the project coordinator every three months and provided to the European Commission.

Detailed financial reports (CS) were provided to the coordinator every 6 months or at the relevant milestones. They were synthesised by the project coordinator and sent to the European Commission. The coordinator allocated the budgets to the partners after the approval by the European Commission of the technical and financial reports.

The whole project period was divided into 4 main (6 month) periods, and a cost statement (CS) was issued at the end of each period and sent to the Commission for intermediate payment. Each of these 4 periods was divided into two sub-periods for a more accurate internal management. At the end of each sub-period, a progress report was written and sent to the

Commission, and an IQCS (Internal Quarterly Cost Statement) was sent by each partner to the coordinator to survey the budget and expenses. The description of these periods and sub-periods are given in Table 6, before and after the project extension.

The project tasks, which are described in section 2.2, were organised and managed using a Gantt diagram.

A database of the project documents was set up.

2.2 Project work packages and tasks

The complete project was organised into 4 *main* work packages, each of them being divided into more specific work packages (WPs). The WPs were further subdivided into tasks and sub-tasks. Each task consisted of a comprehensive piece of work with a specific deliverable or output for another task. The sub-tasks describe the different steps, mainly consecutive, to fulfil the task. Each specific WP covers one of the main objectives of the project and a basic need in Europe. The main WPs were consistent domains, but had relationships between them.

The detailed organisation of the WPs is described below, where the changes which occurred during the project are mentioned (cancelled tasks are crossed out, added tasks are in italic with an asterisk and enhanced tasks are marked with an asterisk):

WP1. Accurate estimation of static weights using WIM systems

WP1.1. Multiple Sensor WIM (MS-WIM)

a. New and improved theories
- a1. Performance of existing sensors
- a2. Vehicle dynamics and WIM array design
- a3. Prior distribution and identification of signal model parameters
- a4. Bayesian statistical analysis and probabilistic models
- a5. Optimal design and performance of a MS-WIM array

b. Validation using experimental data
- b1. Analysis of previous test data
- b2. Design various multiple-sensor arrays
- b3. Performance evaluation by testing
- b4. Comparison theory/experiment

c. Tests of MS-WIM systems
- c1. Installation of MS-WIM systems
- c2. Calibration of MS-WIM systems
- c3. Assessment of the WIM sensor accuracy
- c4. Data collection with lorries
- c5. Calculate various MS-weight estimates
- c6. Compare estimates and measured static weights

d. Specifications and legal issues
- d1. Requirements for enforcement of WIM

d2. Identify and quantify relevant sources of error
d3. Investigate legal and economic issues and vehicle identification
d4. Develop specifications

WP 1.2. Bridge WIM systems (B-WIM)

a. Increased Accuracy for Typical Bridges (*Multiple presence of vehicles*)*
  a1. Experiment *
  a2. More Analysis *
  a3. Combined System
b. Extension of B-WIM to Orthotropic Decks
  b1. Data collection
  b2. Mechanical model
  b3. Software design *
  b4. Validation on a large scale test
  b5. Operational prototype
c. Extension of B-WIM to Other Bridges
  c1. Concrete Slab Bridges
  c2. ~~Bridges with High Skew~~ Box Culvert
  c3. ~~Box Culvert~~ Influence of Surface Roughness on Accuracy
  c4. Report
  c5. *Improvement of Durability by Development of FAD B-WIM Systems* *
d. Dynamic Analysis for Typical Bridges
  d1. Finite Element Model
  d2. Software Development
  d3. Experimental Test
e. Calibration
  e1. Different Truck Configurations
  e2. Characterisation of Bridge
  e3. Pre-drafting of Report

WP2. Quality, management and exchange of WIM data

WP2.1. WIM data quality assurance

a. Analysis of existing quality systems
  a1. Concept for European use
  a2. Usefulness in cold climate
  a3. Overall comment
b. Site quality
  b1. Basic text
  b2. Typical cold climate parameters
  b3. Overall comment
c. System quality
  c1. Basic text
  c2. Comments and improvements
d. Calibration procedure
  d1. Basic text
  d2. Comments and improvements

e. Data quality
  e1. Basic text
  e2. Comments and improvements

WP2.2. WIM data format and database structures

a. Submitted data format
  a1. Basic text based on work of COST-323
  a2. Proposed data format
  a3. Modification and improvement
b. Harmonisation procedure
  b1. Proposal, based on software relation
  b2. Modification and improvement
c. Description of two database levels
  c1. Information required on the two levels
  c2. Description of aggregation procedures
d. Database management and maintenance
  d1. Proposal for management and maintenance procedures
  d2. Modification and improvement

WP3. Consistency of Accuracy and Durability

WP3.1. Durability of WIM systems in cold climates

0. Preparatory work in advance of the project start
a. Reporting previous experience on the subject matter
b. Inviting WIM manufacturers to the test
  b1. Test planning
  b2. Correspondence with the manufacturers
  b3. Negotiations and contracts with the manufacturers
c. Final decision on test site localisation
  c1. Measurement of road profile
  c2. Analysis, discussion and decision
d. Site preparation
  d1. Establishing an electricity line to the test site
  d2. Establishing telephone line(s) to the test site
  d3. Establishing a weather station at the test site
  d4. Establishing a traffic measurement station at the test site
  d5. Performing ground preparation works
  d6. If necessary: installing thunderstorm protection devices
  d7. Furnishing a big protective container for the equipment
  d8. Remove the equipment, restore the site after test
e. WIM installation
  e1. Sensor installation.
  e2. Instrument installation
  e3. Individual calibration
f. First summer test
  f1. Test preparations, organisation of the test
  f2. Invitation of the participants

- f3. Performing the test
- f4. Collect and report test results

g. Winter test
- g1. Test preparations, organisation of the test
- g2. Invitation of the participants
- g3. Performing the test
- g4. Collect and report test results

h. Second summer test
- h1. Test preparations, organisation of the test
- h2. Invitation of the participants
- h3. Performing the test
- h4. Collect and report test results

i. Random traffic test
- i1. Test preparations, organisation of the test
- i2. Invitation of the participants
- i3. Performing the test
- i4. Collect and report test results

j. Final report
- j1. Planning, discussions with the partners in the WP
- j2. Report writing
- j3. Discussions with the manufacturers

WP3.2. Calibration of WIM systems

a. State of the art report

b. Test of calibration devices and procedures
- b1. Calibration of the MS-WIM sites in France with instrumented vehicle
- b2. Calibration of the WIM systems in Luleå, Sweden
- b3. Analysis of the test results from Sweden
- b4. Analysis of test results from other WPs and from COST323 tests

c. Specification of the calibration procedures
- c1. Panorama of the calibration procedures
- c2. Calibration with statically weighed vehicles
- c3. Calibration with instrumented vehicles
- c4. Calibration by software (automatic self-calibration)
- c5. Other methods
- c6. Synthesis and conclusions

WP4. Optical WIM systems, technology for the future

WP4.1. Sensor Design

a. Feasibility

b. Characterisation and testing

c. Calibration

d. Mathematical model (1)

WP4.2. Optoelectronic Head

a. Design
b. ~~Multiple sensor head~~
c. ~~Long-term performance~~
d. ~~Prototype improvements~~

WP4.3. Data Acquisition and Processing Unit

a. Data acquisition and treatment
b. Mathematical model (2)
c. Validation and Report

In addition, a WP0 was designed to cover the project management :

WP0. Project Management

WP0.1. Management by the coordinator and the contractors

WP0.2. Mid-Term Seminar

WP0.3. ***Presentation of the WAVE project on the European WIM Web site ****

WP0.4. ***Editing of a CD-ROM ****

WP0.5. ***Final Symposium ****

* *Additional tasks which were set up during the project and supported by some fund reallocation*

The reduction of the work to be done by Alcatel CIT, outside the WP4, was the cancellation of the contributions to WP1.1 and WP3.1 with the FO-WIM systems. The additional or enhanced tasks costs were covered by the funds left by Alcatel, and re-allocated to other partners (see § 2.3). ETH also did not fulfil its initial requirement in the WP1.1.

Table 7 shows the involvement of each partner in the various tasks. Each WP worked towards providing more efficient and accurate WIM systems and more reliable traffic load data, and they were complementary. WP3 was crucial for all the other WPs, but also took advantage of the extensive tests carried out in them. WP2 depended on the other WPs. WP4 delivered a single-sensor WIM system. Due to technical delay, it was neither possible to perform the long-term performance test in cold climate (in WP3.1), nor to develop a fibre optic multiple-sensor system (in WP1.1).

Partners' involvement in each WP and tasks

WP	tasks	LCPC	CUED	TCD	DWW	Alcatel	SNRA	BRRC	TUM	VTT	ETH	ZAG
1.1	a	x	x								0	
	b	x	x								0	
	c	x	x			0				x	0	
	d	x	x								0	
1.2	a			x+					x			x+
	b	x+		x+								
	c			x+					x+			x+
	d	x							x			
	e			x								x
2.1	a	x			x		x					x
	b	x			x							x
	c	x			x							x
	d	x			x							x
	e	x			x		x					x
2.2	a	x			x		x	x				x
	b	x			x		x	x				x
	c	x			x		x	x				x
	d	x			x			x				x
3.1	0						x			x	x	
	a						x					
	b						x				x	
	c			x		0	x			x	x	
	d						x					
	e			x		0	x					
	f			x		0	x			x	x	
	g			x		0	x			x	x	
	h					0	x			x	x	
	i					0	x			x	x	
	j			x		0	x			x	x	

WP	tasks	LCPC	CUED	TCD	DWW	Alcatel	SNRA	BRRC	TUM	VTT	ETH	ZAG
3.2	a	x	x	x						x	x	
	b	x	x				x			x		
	c	x		x				x		x	x	
4.1	a	x				x						
	b	x				x						
	c	x				x						
	d	x										
4.2	a					x						
	b					0						
	c	0				0						
	d					0						
4.3	a	x				x						
	b					x						
	c	x				x						
0.1		x	x	x	x	x	x					
0.2		x		x	x							
0.3												x+
0.4								x+				
0.5		x+		x+								

Table 7: Partners' involvement in each WP and task

Legend: x = participant x+ = participant with enhanced work 0 = cancelled participation

2.3 Project means and budget

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 part-time in WAVE. A full time assistant project manager was appointed by the coordinator for the duration of the project period, to perform the administrative and accounting work. The total time spent on the project was nearly 30,000 man-hours, i.e. 20 man-years. Figure 2 shows the breakdown of the man-hours by organisation and WP.

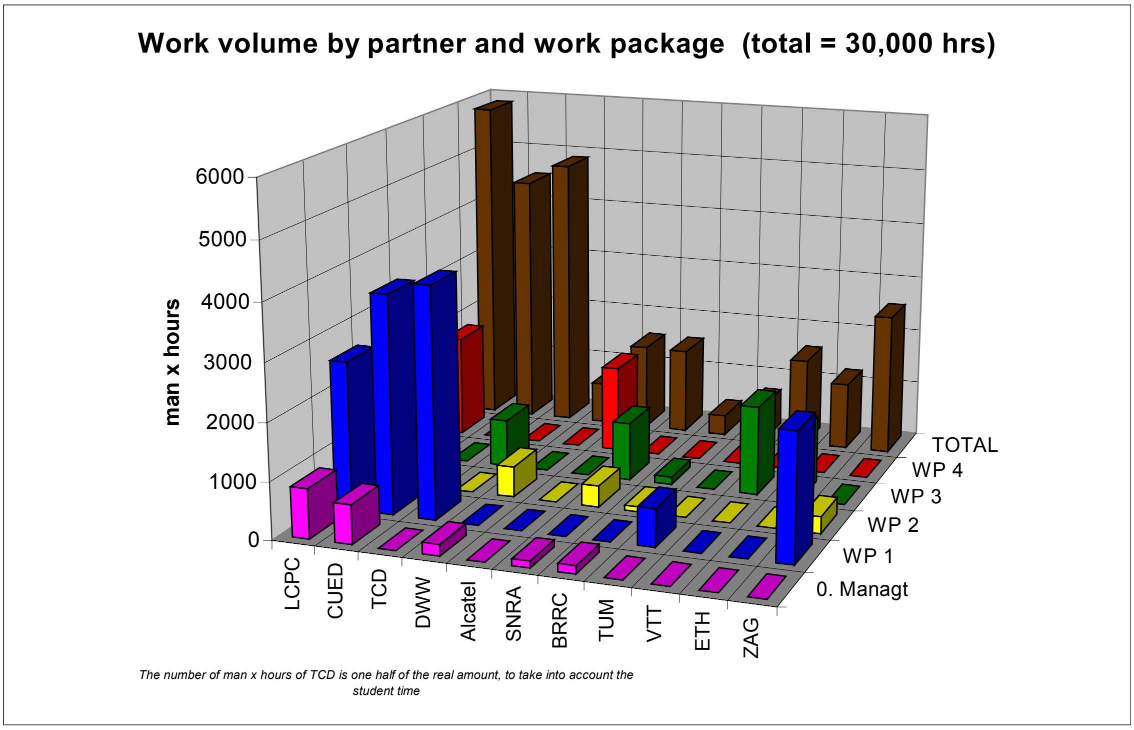


Figure 2: Breakdown of the work volume

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. The WP0 represents the management of the project, as well as the publicity and dissemination activities. The personnel cost represents 69% of the total budget.

Figure 4 shows the total budget and the EC funds by organisation. The organisations which are at "full cost" (LCPC, DWW, Alcatel, SNRA, BRRC, VTT and ZAG) were funded by the EU at approximately 50% of the total cost. The universities (CUED, TCD, TUM) were funded at 100% of the "marginal cost", i.e. excluding the cost of permanent staff. ETH (CH) was not directly funded by the EU, but by the Swiss Government, on the same basis as the other partners, and at "marginal cost".

The initial total budget of Alcatel was reduced by 35% (77,000 Euros), while the new tasks WP0.3 (6000 Euros) and WP0.4 (10,000 Euros) were funded by re-allocation to ZAG and BRRC. The remaining 61,000/2 = 30,500 Euros of EU funds were re-allocated to LCPC, TCD, ZAG and TUM for the enhanced tasks of the WP1.2.

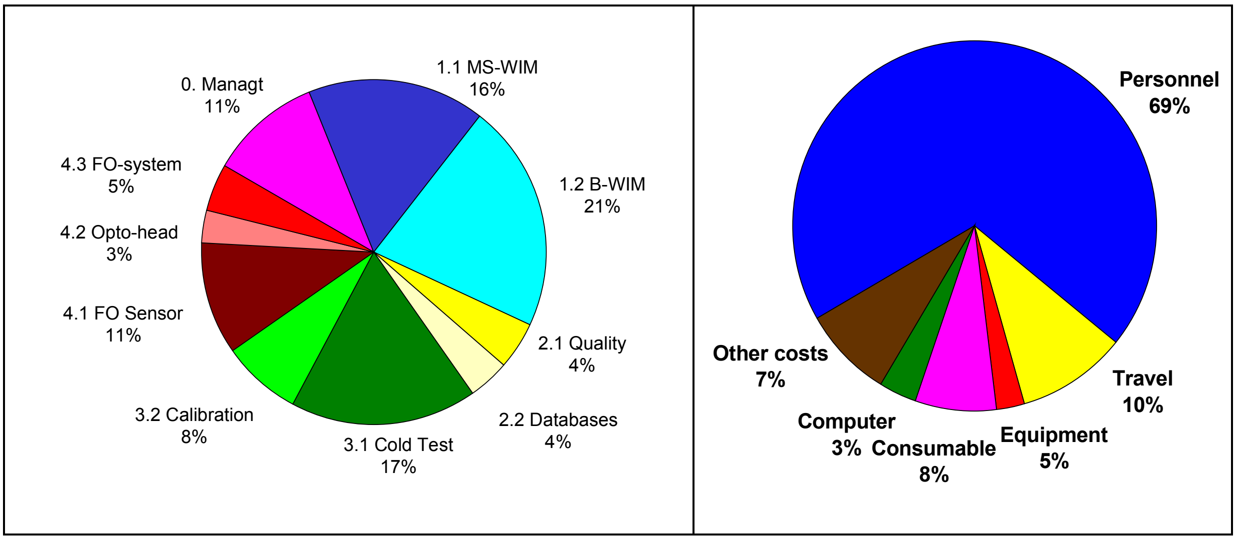


Figure 3: WAVE budget by WP and type of cost

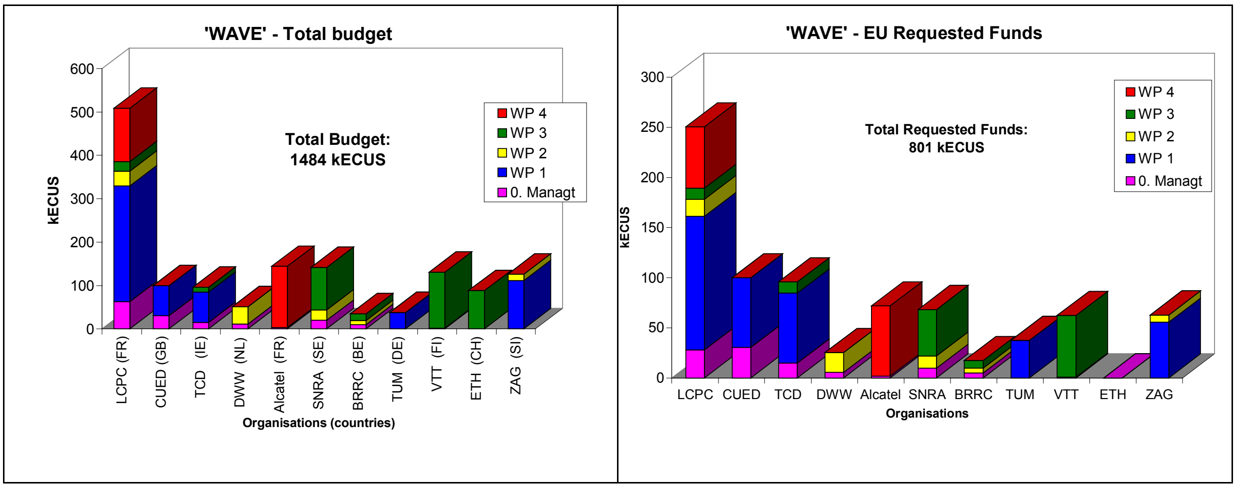


Figure 4: Final budget by organisation (total and EU funds)

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

2.4 Links with other projects

The project had some links with the OECD DIVINE project (1993-97), on Dynamic Interaction between Vehicles and INfrastructures Experimentation. Above all, the Element 5 of this project on Spatial Repeatability of Axle Loads on a Pavement, led by the LCPC (Jacob and Dolcemascolo, 1997), investigated a lot of issues related to the influence of the pavement roughness and the vehicle dynamics on the axle and wheel impact forces applied to the road surface (Jacob 1995; O'Connor and Jacob 2000). Some findings were useful for the design of the multiple sensor WIM arrays and to develop the algorithms of MS-WIM systems (WP1.1). Two MS-WIM arrays used in WAVE, in the UK (Abingdon) and France (RN10, Trappes) were either installed or partially installed by the TRL and the LCPC for DIVINE. The measurements and data analysis done by these organisations provided a strong experimental basis for WP1.1. The output of Element 6 of DIVINE on Dynamic Interaction between Moving Vehicles and Bridges was also used for WP1.2, in order to better take into account the dynamic effects on B-WIM.

As explained in chapter 1, the COST323 action (WIM-LOAD) provided a lot of useful background to WAVE (Jacob, 1998a, b). Among others, the Analysis of Needs and Requirements for WIM (COST323, 1997), the European Specifications on WIM (COST323, 1999), the large scale and long term performance tests of WIM systems (Zurich, Continental Motorway Test - CMT -, and Cold Environment Test - CET -) (Caprez et al. 2000, de Henau and Jacob 1998; Stanczyck and Jacob 1998; Jehaes and Hallström 1998; Jacob and O'Brien 1999), and the European Database of WIM were either used in WAVE or supported some WPs. Further, the First European WIM Conference (COST323, 1995), organised by COST323, provided a valuable service to the WAVE project in establishing the state-of-the-art and the Second European WIM Conference provided a forum for the dissemination of the WAVE results (COST323, 1998a, b, c).

The National French project on WIM, carried out between 1989 and 1993, and led by the LCPC, brought some background on MS-WIM and FO-WIM (Jacob, 1996). The feasibility study and the first design and experiment of fibre optic WIM sensors were done in this project with the research laboratory of Alcatel.

The North American LTPP (Long Term Pavement Performance) programme also used a lot of WIM data and studied the quality of such data (Hallenbeck, 1995a). A Quality Assurance system was developed in the US for that (Hallenbeck, 1995b). It provided some basis and fruitful information for the WP2.1.

3. DESCRIPTION OF THE TECHNICAL WORK

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

Improving the accuracy of WIM systems is an important objective. Most of the applications of WIM would take advantage of an improvement of accuracy, but, particularly, it would allow for enforcement and legal applications (Dolcemascolo and Jacob 1999; van Dijk 1999). The main way of improving the accuracy of WIM systems consists in using multiple sensor WIM systems (WAVE 2001-1). However, the improvement of calibration methods (WAVE 2001-5) was also studied in the project.

A large part of the research in WAVE was dedicated to development of improved Bridge-WIM systems (WAVE 2001-2), where bridges are used as large WIM scales. Those systems allow, in some circumstances, a real improvement in the accuracy of weight estimation (O'Brien et al., 1999). This work is presented in section 3.3 as a new technology.

3.1.1 Accuracy of WIM systems

The COST 323 Management Committee (Jacob, 1998b) developed European Specifications (COST 323, 1999) for representing the (statistically-based) accuracy and performance of any WIM system (Jacob, 2000). The accuracy of the system is defined by an 'accuracy class' described by a letter along with a weight 'tolerance (%)' (confidence interval width) in brackets: A(5), B+(7), B(10), C(15), D+(20), D(25) or E(x), where x = 30, 35, etc.. For example B(10) means that at least a specified proportion π_0 of the individual gross weight WIM measurements will be within ±10% of the static gross weight. Corresponding tolerances for the other criteria (single axles, axles of group and groups of axles) are also specified. The confidence interval width depends on the accuracy class and the type of measurement (e.g. single axle, group of axles, etc), while the confidence level π_0 depends on the test plan (number of runs, of vehicles, duration of the test period, etc.).

This accuracy classification is used throughout this report.

3.1.2 Use of multiple sensor systems (MS-WIM)

High Speed (HS-)WIM systems are widely used throughout Europe for purposes such as statistical traffic load survey, traffic management and infrastructure design and maintenance.

Large scale tests, carried out over long time periods have demonstrated accuracy limitations, due, in part, to dynamic tyre forces induced by pavement roughness. A fundamental limitation in the performance of WIM systems is imposed by the dynamic tyre forces due to vehicle-pavement interaction. The aim of this work is to develop new procedures for Multiple Sensor Weigh-in-Motion (MS-WIM) in order to improve the accuracy of weight estimates (Cebon, 1999). Since cost is also an important issue for future implementation of MS-WIM systems, it is necessary to search for a design which balances 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 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 approach. It is based on a simplified modelling of heavy vehicles and uses mathematical signal processing tools.

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

Experimentation has been carried out on different MS-WIM arrays: Metz (FR) and Trappes (FR) for LCPC, and Abingdon (UK) for CUED.

Signal Reconstruction and Kalman filtering (SR Method)

The force applied to a horizontal pavement by an axle *i* of a stationary heavy vehicle equals the static load W_i^{stat} of the considered axle. However, when the vehicle moves along the pavement, the applied force $W_i(t)$ at instant *t* of the i^{th} axle has a dynamic component so that:

$$W_i(t) = W_i^{stat} + f_i^{dyn}(t) \quad (1)$$

Note that the dynamic component can reach significant values (40% of the static load).

The approach consists of three steps. First, a mechanical analysis is performed of some simplified models of vehicles. It allows a family of functions to be found associated with each type of vehicle and with the evenness of the site. Then a reconstruction algorithm for the impact force: $t \rightarrow W_i(t)$, is performed over this set of functions. Finally, an estimation procedure for the static load W_i^{stat} is proposed. The study mainly focuses on the first and third steps, the second one was presented and validated outside of the project (Sainte-Marie 1997; Sainte-Marie et al. 1998).

Mechanical analysis

If one assumes that a heavy vehicle can be represented by an assembly of rigid bodies (tractor, trailer, axles), the virtual work principle allows the equations of motion of the model to be expressed in the form :

$$M\dot{u} + A(x,t,u) = f(x,t) \qquad (2)$$

where u denotes the state vector of the mechanical system, M the mass matrix, x the position of the vehicle along the pavement and f the contribution of the weight of the bodies but also of the evenness and its derivatives. The variable A represents the effect of the suspensions and the different links between the rigid bodies. An equivalent linearisation of equations around the static load position of the heavy vehicle gives:

$$M\dot{u} + A_e(x,t).u = f(x,t) \qquad (3)$$

Comparisons between (2) and (3) have been performed for several types of vehicle and several types of axle, leading or driving, with mechanical or air suspensions. For each situation, the obtained results prove that a two-dimensional linear model provides a good approximation of the experimentally measured impact forces. It is important to note that the problems induced by axle groups (tandem or tridem) or by a linearisation in the limit conditions of loading, are non completely solved at this point in time.

Reconstruction and estimation procedure

The reconstruction is carried out by the means of a sampling algorithm for band-limited signals with respect to a discrete transform: the algorithm, called ACT (Adaptive weights Conjugate gradient Toeplitz method) was used and proved to be efficient, robust, and stable.

In order to validate the reconstruction procedure, one records measurements of the impact forces of an instrumented truck, whose mechanical characteristics are unknown, when its axles run over a sensor array. Tests were carried out with simulated signals given by an instrumented truck. Results are shown in Figure 5.

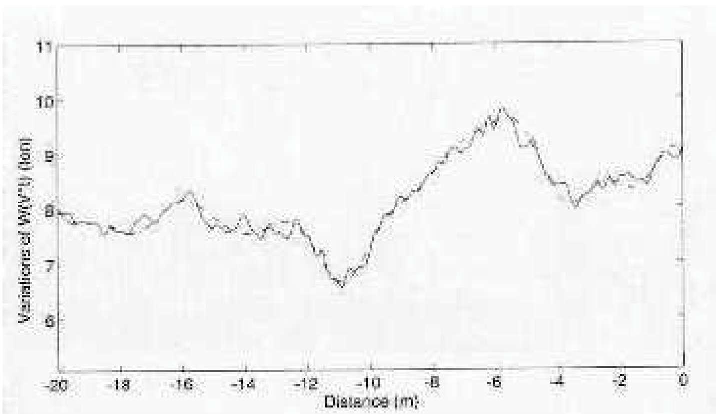


Figure 5: Variations of the impact force for the second axle of a 5-axle truck for n = 4, (–) experimental measurement, (-.) reconstruction algorithm.

It was proved that dynamic forces were well approximated by a function interpolated from a set of sample measurements.

Next, the reconstruction step is used to obtain a static load estimation of an axle based on a quadrature of the reconstructed signal $t \rightarrow W_i(t)$. Let f_1 and f_2 be the natural frequencies associated with rolling and bouncing vibrations respectively. For each axle, f_1 and f_2 are in fact estimated by Kalman filtering.

We define T by:

$$T = \frac{p}{f_1} \approx \frac{q}{f_2} \tag{4}$$

where p, q are integers such that $V * T$ has approximately the same length as the sensor array, V being the mean speed of the vehicle over the array. Then, the static load estimation is given by:

$$\left[W^{stat}\right] = \frac{1}{T} \int_T (W_i(t) - W_a(t))dt \tag{5}$$

where W_a denotes the aerodynamic effects over the first two axles of each vehicles.

The accuracy of this static load estimation procedure has been tested with pre-weighed heavy vehicles from the traffic flow.

In the same conditions with the same set of trucks, it was shown (Sainte-Marie, 1999) that the accuracy class B+(7) was obtained, with δ_m = 9.2 and δ_m = 8.6 for 6 and 12 sensors respectively, if δ_m denotes the minimum confidence interval according to the considered tests conditions.

Experimentation with an instrumented truck showed that, if the sensor error is neglected, the reconstruction method may be very accurate. The static axle weight was estimated within ±3% with 9 sensors, and ±2% with 13 sensors.

The Maximum Likelihood method (ML Method)

Before discussing the Maximum Likelihood approach it is necessary to review previous results from the Sample Mean method.

Overview of the Sample Mean (SM Method)

- **The sine wave model:** The dynamic forces are modelled as the sum of sine waves. There are two types of oscillation modes: low frequency body pitch and bounce vibration modes (*f1*), and axle hop vibration at a high frequency (*f2*).

  Two simple generic vehicle models, representative of the two main classes of suspension, were chosen. The first is a quarter car model (80% of trucks) for air or leaf-spring suspension, for which the tyre force spectrum can be approximated by a single sinusoid of low frequency. The second is a walking beam model (20% of trucks) for axle group suspensions, for which the tyre force spectrum can be approximated by two sinusoidal components.

A general model of M sine waves can be completely described by $3M+1$ parameters:

$$F(t) = F_0 + \sum_{i=1}^{M} F_i \sin(2\pi f_i t + \phi_i) \tag{6}$$

F_0 is the mean level (which is assumed to be the static weight). For simulation purposes, random uncorrelated noise $n(t)$ can be added to account for the errors in the signal model and the errors introduced in the measurement process.

- **Sample Mean approach:** For a single sine wave, the Sample Mean estimate $\overline{F}$ of the static weight from N sensor outputs F_k is given by :

$$\overline{F} = \frac{1}{N}\sum_{k=1}^{N} F_k = F_o + \frac{F_1}{N}\sum_{k=0}^{N-1}\sin(2k\pi\delta + \phi) + n_k \tag{7}$$

where n_k is the measurement error for the k^{-th} sensor.

The worst-case 'envelope' error is:

$$\varepsilon_e = \pm\left(\frac{1}{N} + \frac{2}{N^2}\sum_{k=1}^{N}(N-k)\cos(2k\pi\delta)\right)^{1/2} \tag{8}$$

The regions for δ with small envelope error give an optimal value for spacing :

$$\Delta_{d_1} = \frac{2(N-1)\overline{V}}{\bar{f}\,N^2} \tag{9}$$

The design procedure simply involves choosing the number of sensors N and calculating the sensor spacing for the assumed average speed (Figure 6).

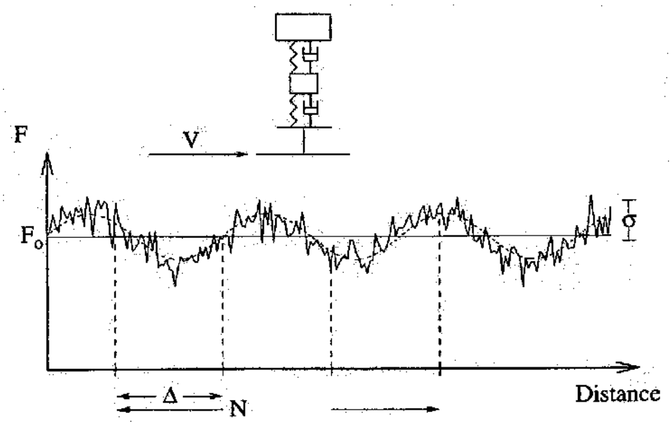


Figure 6: Impact force signal and design spacing

The Maximum Likelihood Method (ML)

ML is an unbiased method (bias is neglected); only RMS errors are important.

The ML algorithm fits the signal model parameters by finding those parameter values (f_0, F_1, f_1, Φ_1,…) that maximise the associated Likelihood function (Kay, 1988).

Using finally the non linear least squares method, one obtains:

$$F(t) = F_0 + \sum_{i=1}^{M} (F_i \sin(\phi_i)\cos(2\pi f_i t) + F_i \cos(\phi_i)\sin(2\pi f_i t)) \tag{10}$$

The method can be used for both regular and irregular sensor arrays and behaves well in the presence of sensor noise.

The minimum number of sensors required for the solution of the ML calculation is equal to the number of signal model parameters, i.e., $3M+1$.

Analysis of the estimation error and optimal spacing

- **Sample Mean performance for a single tone :** The Sample Mean result is always biased, and the estimation error will be given by:

$$\hat{\varepsilon}_e = \frac{\sum_{i=0}^{N-1} F(t)}{N} - F_0 \tag{11}$$

  with standard deviation: $\sigma_n / \sqrt{N}$.

- **ML performance: Cramer-Rao bounds:** The unbiased Cramer-Rao Bounds (CRB's) are the diagonal elements of the inverse of the Fisher information matrix.

  It is shown for a ***single tone (ML1)*** that, for the ideal case of noise-free sensors sampling of a perfect sine wave with a sufficient number of points and no aliasing, the ML error is exactly zero.

  The Error Coefficient of Variation (ECOV) (Cebon, 1990) is:

$$\rho = \frac{\sigma_e}{F_0} \tag{12}$$

  In the case of single sensor systems, the ECOV is equal to the Dynamic Load Coefficient (DLC) which characterises the dynamic tyre force (Sweetman, 1983; Cebon, 1990).

  The ML algorithm requires that the sensor array should be longer than one cycle of the lowest frequency component.

  This analysis suggests that the error of the biased SM estimate worsens as the dynamic tyre force increases, whilst ML performance remains unaffected.

  The ML approach is robust and insensitive to variations in vehicle speed and resonant frequencies within its operational limits.

  For ***two tones (ML2)***, CRB's for two sufficiently separated tones approach the corresponding single-tone analysis.

From the single-tone analysis, it is concluded that a good design strategy would be to set the design sensor spacing at:

$$\Delta_{d_2} = \frac{\overline{V}}{2N}\left(\frac{1}{\bar{f}_1} + \frac{N-1}{\bar{f}_2}\right) \tag{13}$$

The limit on the minimum possible number of sensors is:

$$N \geq Smaller\,of\left(\frac{f_2}{f_1} + 1;\ 3M + 1\right) \tag{14}$$

The ratio of frequencies is very important. In practice, it will be set by the types of vehicle using the road (in particular, their suspension and tyre types and the masses of their axles and bodies (Cebon, 1999).

Simulation results

The Quarter Car model is compared to the Sample Mean (SM) method, in both noiseless and noisy cases. The ML1 error is generally less, producing a relatively smooth plateau region over a wide range of spacings. However the relative benefits of ML1 are significantly less in the noisy case. ML1 seems to be less sensitive to variations of the resonant frequency and the vehicle speed than SM.

The Walking Beam model (ML2) allows a relative improvement which is even greater in this case than in the quarter car case. The ML2 algorithm is relatively insensitive to variations of the vehicles speed and the resonant frequencies in this case also.

Success rate of the weight estimation algorithm

The success of the data processing algorithms is dependent on having correct sensor spacing. The analysis is general and can be applied for any WIM estimation method that requires efficient sampling.

The probability of failure is:

$$P_F(N;\Delta) = Q_2(N\Delta) + Q_1\left(\frac{N}{N-1}\Delta\right) \tag{15}$$

$Q_1(\lambda)$ being the probability that the ratio V/f of the two independent Gaussian variables (f,V) is less than a given threshold λ, and Q_2 the probability that the ratio V/f of the two independent Gaussian variables (f,V) is greater than λ.

At the typical level of noise for good sensors, $\sigma_n/F_0 \geq$ 4%RMS (Cebon and Winkler, 1991a) - ML estimation is not that much more accurate than the SM.

Experimental studies on MS-WIM sites

Experiments were performed on two MS-WIM sites in France (Trappes and Metz) and on one MS-WIM site at Abingdon (UK). Data previously collected in the USA by researchers from CUED and the University of Michigan, with a load-measuring mat were also considered.

Errors and calibration

Careful calibration is critical for WIM accuracy. There are two main calibration methods for WIM arrays (see discussion by Cebon (1999)). Both involve driving one or more calibration vehicles over the site and comparing the sensor outputs W_{d_i} with reference loads W_{s_i}. The reference loads may be either: (i) static loads (measured on a static weigh-scale) of various axles; or (ii) dynamic tyre forces measured by an instrumented axle (Cebon, 1999). In this latter case, care must be taken to synchronise the measurements taken on-board the instrumented vehicle with the data collected from the WIM array.

The MS-WIM array at Trappes (FR) - Sample Mean Method

An MS-WIM array was installed on the slow lane of the national road RN10 near Trappes in May 1994 for the OECD/DIVINE project (Jacob, 1995). The test site was chosen because its pavement and traffic conditions are representative of European highways. The mean speed of the vehicles passing on the RN10 is 80 km/h.

The pavement and road conditions fulfil the requirement of a class II (good) WIM site, according to the COST 323 specifications (COST 323, 1999). The array consisted of 24 piezo-ceramic strip sensors (bars) and 7 magnetic loops. The bars were placed at non uniform spacings (Figure 7).

Figure 7: Picture of Trappes MS-WIM array, RN10, France

Approximately 100 lorries, representative of the whole traffic flow, were stopped on a weighing area 5 km upstream of the test site, and weighed statically on an approved enforcement scale. Each of these lorries passed the MS-WIM system at normal traffic speed. This sample provided results in 'full reproducibility' conditions (R2) (COST323, 1999). Moreover, this trial was carried out in 'environmental repeatability' conditions, because of the short test duration and the constant climatic conditions.

On the Trappes MS-WIM site, a major part of the experiment concerned the analysis of the accuracy of the individual sensors and the accuracy obtained with several combinations of sub-arrays.

After the final calibration, data analysis showed that the individual sensors were in classes C(15) or B(10), and two in class D+(20) (after elimination of four more whose accuracy was too low).

In order to investigate the influence of the sensor number and spacing on the accuracy, 14 sub-arrays (MSA) were considered. The sensors should be placed at a uniform spacing to avoid any bias due to spatial repeatability; and the length of the array should be longer than the longest wavelength generated by vehicle motion (Jacob and Dolcemascolo, 1997). Therefore, only the uniformly spaced sensors at 2.25 m were considered.

The minimum spacing of 2.25 m in this array is somewhat different to the design spacing given by Equation 9, which is Δ_{d1} = 1.45 m. However, the MS-WIM array on RN10 was initially designed for investigating 'spatial repeatability' (O'Connor and Jacob, 2000), as part of the OECD/DIVINE project (Jacob 1995; Jacob and Dolcemascolo 1997). This explains why a sub-optimal spacing was used.

For each sub-array, the individual static axle loads were estimated using the Sample Mean (SM) of the measurements on the sensors considered, while the group of axle loads and gross weights were obtained by summing the appropriate axle loads.

The accuracy verification was made for each sub-array using 84 pre-weighed lorries sampled from the traffic flow, which passed on the MS-WIM system. Using independent samples for the calibration and the accuracy check, allowed an in-service verification.

The main findings were:

(i) The differences between the various sub-arrays were relatively small. For the gross weights, the Δ_{min} values were all between 6.6% and 7.7%, except for one at 8.7%.

The length of the sub-array is of great importance for the gross weight accuracy. The longest arrays (over 27 m) were the most accurate, in class B+(7). This length must exceed, as far as possible, the longest wavelength of the dynamic tyre force signal, in order that the averaging procedure smoothes the bias resulting from the spatial repeatability for individual vehicles.

(ii) The effect of the longitudinal location of the sub-array was low. This means that the influence of 'statistical spatial repeatability' (Jacob and Dolcemascolo, 1997) is not significant for a well calibrated MS-WIM system.

(iii) Almost all the sub-systems met the requirements of accuracy class B(10) for the four criteria, while one was in class B+(7) for three criteria. A few more sub-systems were in class B+(7) for two criteria. The sub-array which contains 3 low-accuracy sensors (class D+(20)) out of 5 was the less accurate - in class C(15). Therefore, on such a class II site, it appears that, with 5 to 7 sensors individually in class C(15), on average, an MS-WIM system in class B(10) can be achieved. With 13 sensors, class B+(7) can almost be achieved.

(iv) The best compromise between the number of sensors (cost) and accuracy seems to be for the sub-array which has 5 to 7 sensors at 2.25 m spacing. However the sensor spacing is less than the theoretical value of Δ_{d1} computed by Equation 9 which is about 4 m. It should be noticed that robustness is not ensured with such a small number of sensors and short spacing: for all the 5-sensor arrays with a spacing of 2.25 m, the mean and standard deviation of δ_{min} are 7.43 and 1.25 respectively, with values between 6.7 and 8.7. Such arrays are too short (9 m) compared to the wavelength of the impact force signal, which exceeds 12 m.

(v) The performance of the Sample Mean method is limited by the individual performance of each sensor. Instead of increasing the number of sensors, it would likely be better to improve their performance, by a better calibration, or improving the signal processing methods, or using more accurate sensors.

The MS-WIM array at Metz–Obrion (FR)

The test site at Obrion is situated on the A31 motorway, in the south-bound direction (Luxembourg-Nancy), on the slow lane (Figure 8).

Figure 8: Picture of Metz MS-WIM array, A31, France

The site is classified as a class I (excellent site) in the European specification for weigh-in-motion (COST 323, 1999). The WIM system consists of 16 piezo-ceramic strip sensors spaced by 1.6 m, linked to a Hestia data logger supplied by the ECM company.

On the A31 MS-WIM test site, some calibration measurements were carried out in June 1998 with an instrumented lorry supplied by the VTT, as part of the WP 3.2 of WAVE. The calibration of each sensor of the MS-WIM array is described in detail in the WP3.2 report.

Sixteen sensors were used at the site because the theory described above (Sainte-Marie et al., 1998) showed that it is theoretically possible to reach an accuracy of 1 or 2% of the static weight with an MS-WIM array consisting of 13 or 15 sensors. However, for practical reasons due to the electronic and sensor detectors, an even number of sensors was adopted, and 16 was the maximum number allowed by the Hestia data logger design. The mean traffic speed on the site was 25 m/s (90 km/h). The mean bounce motion frequency of vehicles was estimated to be $f = 1.8$ Hz, because of the predominance of air suspensions. The sensor spacing was selected using Equation 9 and was $\Delta d1 = 1.6$ m.

However, after a couple of months of measurements, the individual accuracy of the sensors (between C(15) and E(35)) was not in accordance with the expected performance of sensors installed on a Class I site. Some experiments were performed to investigate the errors: the electronic WIM stations were tested and also the pavement deflection was measured. Following this, a few sensors were replaced but no explanation was found from these investigations. Some further analyses were performed at the end of the project, with the participation of the manufacturer (ECM). Finally it was proven that the errors resulted from a combination of two causes:

- the lorries on this heavily trafficked motorway are travelling close to the right emergency lane, i.e., close to the right margin of the slow traffic lane, because of the high vehicle density on the left passing lane;

- the WIM bars were either too short or centred in the traffic lane, and thus a significant proportion of the right wheels were passing outside or partially outside of them.

This resulted in some large errors in the WIM measurements of some vehicles, which induced a wrong self-calibration of the whole WIM system. The manufacturer (ECM) was finally asked to replace all the initial sensors, in order to account for the site traffic conditions.

The sub-arrays were used for the comparison of the Sample Mean (SM) and Signal Reconstruction (SR) algorithms. Each sub-array was chosen to be as long as possible. The Signal Reconstruction method required all the sub-arrays to have an odd number of sensors.

Concerning the SM method, the results were generally disappointing. No sub-array achieved better than Class C(15) for any of the criteria. This can be attributed to:

(i) the low accuracy of the individual sensor measurements,

(ii) the fact that the spacing of the sensors in the sub arrays was, for the most part, significantly different from the theoretical design value $\Delta d1$, calculated using Equation 9. The exceptions were the arrays with 3 and 5 sensors. However these arrays are expected to be the least accurate.

Because of the poor performance of the sensors of the array at Metz (Obrion), which led to disappointing results with the sub-arrays and the Sample Mean method on such a good site, it was decided not to apply any new MS–WIM algorithms with these data. Only the data collected on the RN10 in Trappes were used. However, LCPC are still endeavouring to up-grade the MS-WIM array in Metz and ECM have been asked to effect the sensor replacement.

Data collected with Load Measuring Mat (UK)

Data collected previously with a wheel load measuring mat (Cebon and Winkler, 1991a and b) was re-analysed to investigate the accuracy of the Maximum Likelihood method. The mat incorporated 1.2 m long capacitive strip sensors which were encapsulated in stiff polyurethane tiles of dimensions 1.2m x 1.2m x 13mm thick. Each tile had three sensors, laid transverse to the wheel path at a spacing of 0.4 m between sensors. The mat had 32 tiles, (a total of 96 sensors), which were mounted end-to-end on the road surface, to provide an instrumented test section of length 38.4 m along one wheel track. The polyurethane mat tiles were attached to the road with a sheet of double-sided adhesive tape and 12 masonry anchors per tile, screwed into the road surface. Golden River ‘Marksman 600’ data loggers were connected in a serial data network, from which data was uploaded to a personal computer.

For either algorithm (SM or ML1), the MS-WIM systems with 5 or 7 sensors achieved class B(10) for spacing of 2.5 to 5m. Systems with 8 or 9 sensors can reach class B+(7) under some conditions. This corresponds to an RMS measurement error of less than 4%, which compares with an average error of approximately 2.7% (for the noisy sensors).

In general it can be seen that the results for the Sample Mean (SM) and ML1 algorithm are similar. In fact, ML1 performs slightly worse than SM for many conditions. The main reason is that the baseline sensor noise level, (measured to be 4%), is sufficient to degrade the performance of the ML1 algorithm. (This result was predicted by the simulation study).

SM seems to give similar accuracy to ML2, but ML2 is always slightly worse than SM, particularly for 9 or 10 sensors. In these cases the ML algorithm becomes inaccurate (divergence of the Cramer Rao bounds).

The disappointing results given by the ML algorithm relative to SM, are due to sensors noise which make it inappropriate.

The MS-WIM array at Abingdon (UK)

A site on the North-bound carriageway of the A34 trunk road near Abingdon, Oxfordshire, UK, was chosen for the experimental component of WP1.1 performed in the UK. The location was at the downstream end of a ‘lay-by’ between junctions A413 and A415. A weigh station, run by the Vehicle Inspectorate, is located at junction A415. The road surface was asphalt, with some evidence of minor wheel–path rutting (Figure 9).

The parameters assumed for the experimental array design were as follows:

$V = 20$m/s (72 km/h); $f_1 = 2.5$ Hz, $f_2 = 12$ Hz; $N = 10$.

From Equation 13, the design spacing was calculated to be 1.1 m. Using the method described above, it was estimated that with this spacing, it should be possible to measure the axle loads of most vehicles travelling in a speed range of 18 m/s to 22 m/s (64-80 km/h).

During the grinding process, it was found that some sections of the traffic lane were more heavily rutted than observed in the initial site survey - with approximately 8 to 10 mm deep ruts. This meant that even after the 'grindable' part of the sensor carrier was completely removed (about 6 mm), the top of the carrier was proud of the road surface in the wheel path, by up to 2 mm. Approximately half of the sensors suffered from this problem. From previous work this was known to be a significant source of inaccuracy for WIM measurements (Cebon, 1999).

As a consequence it was decided to fill the space between the sensors with a thin layer of adhesive-based resurfacing compound, so as to bring the surface as near as possible to flush with the sensors. Installation of the compound involved preparing the surface, trowelling on the adhesive in the spaces between the sensors, covering the adhesive with fine chippings and allowing the adhesive to cure. This provided a very durable running surface (Stergioulas and Cebon, 1999).

Unfortunately the problem was not entirely solved, and noticeable surface roughness with a 1.1m wavelength remained on the site after the treatment. This excited the dynamics of passing vehicles, and undoubtedly decreased the accuracy of sensor measurements on the array.

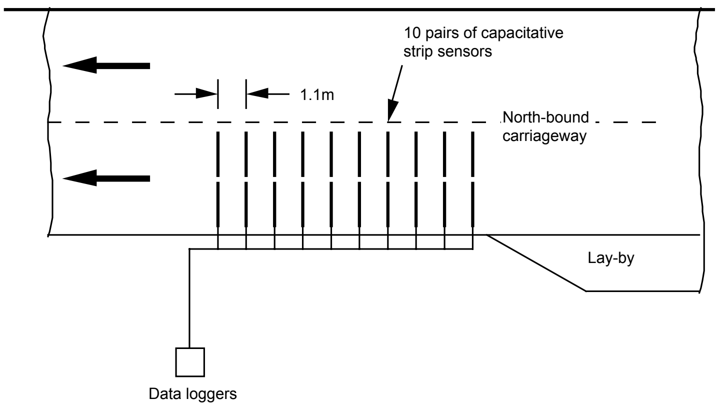


Figure 9: MS-WIM array in Abingdon, Oxfordshire, UK

Calibration was performed using a 4-axle tractor semi-trailer vehicle, provided by the TRL.

The errors in dynamic load measured by the calibration vehicle were estimated to be approximately 3% RMS: double the values obtained previously under more favourable conditions, because of the surface roughness, and estimation of the value of mass and roll moment of inertia of the wheel and axle components. The average RMS error between sensor measurements and dynamic tyre forces for all 18 functioning sensors was 9.26%. Assuming that the errors generated by the vehicle instrumentation and the WIM sensors are uncorrelated, the average RMS WIM sensor error can be estimated to be 8.8%. This value is much higher than the 4% expected, mainly because of rutting.

11 vehicles were randomly selected for data collection.

The following can be observed:

(i) the three algorithms (SM, ML1 and ML2) have essentially the same accuracy for large numbers of sensors,

(ii) the measurement bias is approximately 7 - 10% for all estimation methods – probably as a consequence of calibration drift due to temperature,

(iii) on both plots, the most accurate estimates are obtained by ML1 with Δ=2.2 m. The reasons for this are not clear.

Unfortunately there were insufficient weight samples to obtain meaningful information from the COST 323 weight accuracy classes for this population.

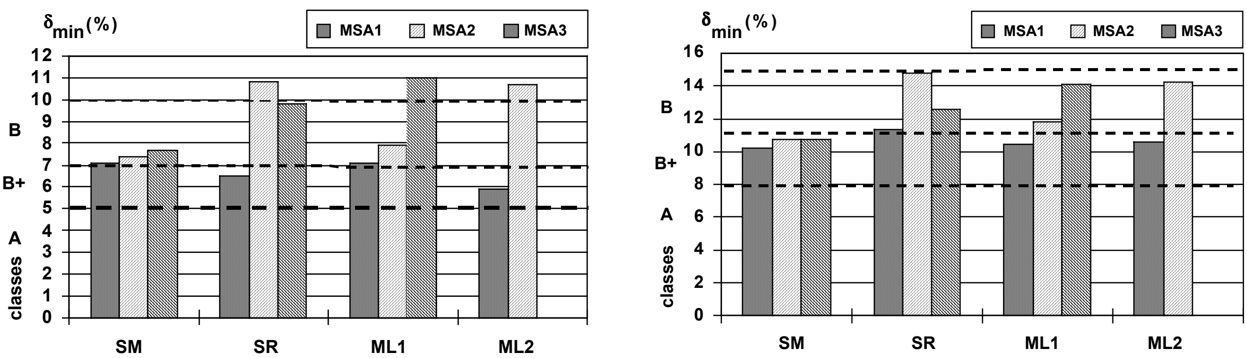
Conclusions: comparison of the new algorithms using the Trappes MS-WIM array

This section compares the performance of the various algorithms developed by LCPC and CUED using data recorded on the MS-WIM array on highway RN10 at Trappes.

Among the set of 100 pre-weighed vehicles, it was decided to compute the performance of each method using 20 vehicles with single axles and three sub-arrays (Table 8). Figure 10 shows the effects of the sub-arrays on axles loads and gross weight.

Sub–array	No sensors n	Spacing	Δ_{d1} (m)	Δ_{d2} (m)
MSA1	16	2.25m	1.45	1.25
MSA2	13	2.25m	1.75	1.32
MSA3	7	2.25m	3.0	1.67

Table 8: Sensor spacings for the arrays used in the comparative tests



(a) (b)

Figure 10: Estimation of Gross Weights (a) and Single Axles Loads (b) for a 2-axle rigid lorry (T2) and an articulated semi-trailer (T2R2) – Effects of sub–arrays

For the computation of one axle weight, and using a Personal Computer equipped with a Pentium II processor at 100 MHz, the 'SM' method required 2 seconds, the SR method took 4 minutes, and the ML methods 2 seconds (ML1) and 4 minutes (ML2) respectively. That means that the computation of all the axles of the considered sample took 2 minutes for the 'SM' and ML1 methods, and 4 hours for the SR and ML2 methods.

The statistical outliers of the static axle load estimation for the 20 vehicles were detected by the Dixon test at a confidence level of 95%. They were thought to be mainly due to some errors in the methods, sometimes because of a poor convergence. In the whole sample, the SR method had no outliers, the 'SM' method had 0.5% of outliers, the ML1 method had 1.5% and the ML2 19%. These rates give a fruitful indication on the robustness of each method.

The reasons for the large number of outliers for ML2 is that the sensor spacing used in the sub-arrays was unsuitable for this algorithm.

Class B+(7) is always obtained by the 'SM' method for single axle loads. The other methods are more sensitive to the number of sensors. The accuracy of the SR and ML2 methods increases with the number of sensors. ML2 can achieve class A(5) if only the 2-axle rigid trucks are included.

3.1.3 Calibration of WIM systems

As with any measuring device, a WIM system must be calibrated before being used, and recalibrated at periodic intervals, in order to remove any bias. However, the calibration of a WIM sensor/system is never a simple task because experimentation is carried out on different road sites of variable quality and not in a laboratory. Thus calibration results are sensitive to external parameters (climate, road conditions, traffic conditions, etc.). Moreover the calibration cannot be done according to any metrological requirement for several reasons (Jacob and Stanczyk, 1999). For example, there is no metrological definition of an axle/wheel weight, as an axle/wheel does not, in any meaningful way, have mass, except as a part of a vehicle when dismantled. A static axle force is the sum of the forces applied to the road surface by the tyre(s) belonging to this axle/wheel, when the vehicle is stationary. It is not a traceable quantity, because their measurements cannot be checked using standard masses.

An intrinsic cause for inaccuracy in WIM systems is the error induced by mathematical approximations, data processing, etc.. However, the accuracy of a WIM system also depends on the reference used, and thus on the purpose of the data collection. Generally, most of the applications require an estimate of the static weights and thus these static weights are taken as the reference values. As already mentioned, the definition of an axle static load/weight is itself a difficult task. The alternative reference is the intensity of the impact force applied to the road surface by an axle, but as it varies continuously with respect to time and space. Because of the difficulty of getting an instantaneous true value of applied force, it remains a theoretical reference, not easy to use.

Accuracy and repeatability or reproducibility are not well defined and they do not necessarily have corresponding words in other languages. ‘Accuracy’ can be defined as the closeness of a measurement to the true value being measured and repeatability or reproducibility as the closeness with which the measurements agree with each other depending on the test conditions. This can be described graphically as in Figure 11. “Not accurate” can be expressed also with the word “bias”. There is no exact definition for bias but it can be described as the difference between the estimated value and the true value in a statistic obtained by random sampling. “Not repeatable” can be alternatively described with the word “scattered”.

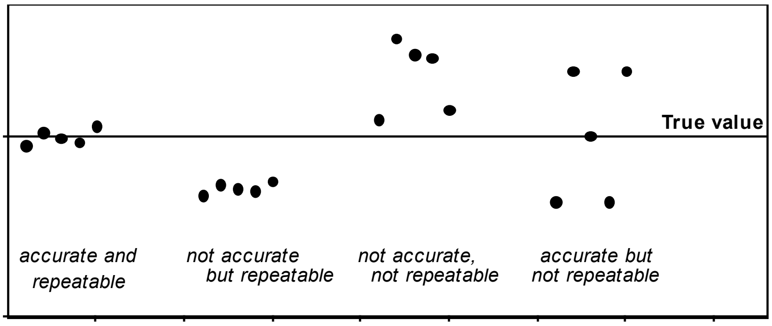


Figure 11: Definition of Accuracy and repeatability/reproducibility

In this report, the factors affecting the accuracy of a WIM system will be outlined. Using the instrumented vehicle as a calibration tool and linking in with an analysis of the experimentation, a procedure for calibration by axle rank will be presented.

Factors affecting the accuracy of WIM systems

Dynamic loading is a factor affecting the accuracy of WIM systems. The main movements of a vehicle are body bounce (*f* between 1.2 and 3Hz), axle hop (*f* around 10Hz). To minimise the effects of dynamics on the accuracy of WIM systems, the road before the WIM system must be as even as possible. Even if it is very smooth, dynamics can cause in excess of ±10% of variation. Harsh weather conditions (wind or ice) may also affect the accuracy of the sensors.

Accuracy also depends on the type of sensor and WIM system:

- Load cell and bending plate: steel or aluminium plate with the whole wheel on the plate. The real tyre force is measured. These systems can be in principle calibrated with calibration masses. The response is usually not dependent on the speed of the vehicle nor the ambient temperature.
- Strip sensors: piezoceramics, piezoquartz, capacitive, fibre optic, etc Because these sensors measure a variation in pressure, the signal from the sensor must be integrated. If the integration is not perfectly done, the result may be sensitive to the speed of the vehicle.
- Portable WIM systems: for temporary use. Usually, it consists of a capacitive mat, capacitive, piezo-polymer or piezo-ceramic strips, which are laid on the road. The extra thickness due to the system induces uncontrolled dynamic effects which have a considerable influence on accuracy.

- MS-WIM: several strip sensors are usually used. Either the Sample Mean or a complex algorithm is needed to average the results in order to eliminate the dynamic effects and estimate the static weight.
- B-WIM systems use totally different methods: a whole bridge span acts as a measuring system. An algorithm is used to deduce the estimated static weight from the influence line. The calibration depends on the type of bridge.

Of course, the calibration method also influences the accuracy. The different methods, also described in (COST323, 1999), are:

- Calibration masses: they can be used only on load cell and bending plates, i.e., on large scales on which standard masses may be applied. They can distinguish possible differences along the plate. These masses do not take into account the effect of dynamic loading, nor the specific tyre impact, and can be used only as the first step of calibration, either in a laboratory or on site. This is the only "fully metrological" calibration process, with complete traceability.
- Calibrated forces or shocks: vehicle wheel load may be simulated with calibrated concentrated load or shocks, such as with a Falling Weight Deflectometer (FWD). This method was tested in the OECD/DIVINE project, Element 5 (Jacob, 1995) but it was proven that it was neither accurate nor easy to implement on site.
- Pre-weighed vehicles: the axle loads are measured statically on wheel or axle scales, and the vehicle(s) pass(es) several times over the WIM system. The payload and speed may be varied. The number of pre-weighed vehicles is usually limited to 2, 3, 4 or 5, of different type (silhouettes), representative of the vehicles to be weighed. That is the most common calibration method for WIM systems, used either for an initial calibration or for an in-service calibration or check.
- Vehicles from the traffic flow: vehicles from the traffic flow are stopped, either before or after passing the WIM system, and their axle loads are weighed. The vehicle weights can be measured either statically or sometimes on a low-speed WIM system of approved accuracy level much higher than that expected from the WIM system to be calibrated. This method is highly recommended for in-service checks.
- Automatic self-calibration procedures: these procedures, initially developed in France (Stanczyk, 1984), use the knowledge that some types of vehicle have quite consistent weights on one or two of their axles; such vehicles are called ‘characteristic vehicles’. If there are enough characteristic vehicles in the traffic flow, it is possible to develop an automatic self-calibration procedure using software which can correct the drift or variations in the sensitivity of sensors due to temperature or other effects. The procedure requires a good knowledge of the site-dependent traffic patterns and the target values must be adapted for each site. The procedure also may introduce a "statistical noise"; the lower the traffic flow (characteristic vehicles), the higher the noise. However, it was proven that this procedure, if correctly implemented, may be very efficient for most types of strip sensor (piezo-polymer, piezo-ceramic, capacitive), whose response is dependent on the temperature, either because of the physical properties of the sensor or through the pavement modulus.

- Instrumented vehicles: some test vehicles are instrumented, mostly with stain gauges and accelerometers, which measure continuously accelerations and strains in some parts of the vehicle. Then, using suitable modelling software and a dynamic calibration, the real dynamic wheel/axle loads are derived with a high sampling frequency (e.g. 200 to 500 Hz). The dynamic load records are synchronised on the WIM sensors using reflective tapes placed on the pavement and an optical system on board the vehicle. Such instrumented vehicles were used to calibrate the MS-WIM arrays. In Trappes, a Canadian 5/6 axle tractor with semi-trailer (Figure 12a) supplied by the CNRC (Jacob, 1995) was used; in Abingdon, an instrumented lorry (Figure 12b) supplied by the TRL (WAVE, 2001-1), and in Luleå and Metz - a three-axle lorry (Figure 12c) supplied by the VTT (WAVE, 2001-5). If the system works well with an accurate synchronisation and reliable dynamic load measurements, this would be ideal for the calibration of WIM systems. However, that was not the case with the VTT lorry (see below).

(a)

(b)

(c)

Figure 12: (a) CNRC instrumented semi-trailer, (b) TRL instrumented lorry, (c) VTT instrumented lorry

- B-WIM system calibration: trucks of known weight (axle loads and gross weight) are used to calibrate bridge WIM systems. Test plan N°2.1 from the European specification of WIM (COST 323, 1999) was recommended.

The European Specification on WIM (COST 323, 1999) describes all these calibration procedures and calibration checks by testing. The following cases, using pre-weighed lorries and vehicles from the traffic flow, are considered, both for initial calibration and in-service checks:

1. Full Repeatability Conditions (r1): one vehicle passes several times at the same speed, load and lateral position.
2. Extended Repeatability Conditions (r2): one vehicle passes several times at different speeds, different loads and with small variations in lateral position (in accordance with typical traffic).
3. Limited Reproducibility Conditions (R1): a small set of vehicles (typically 2 to 10), representative in weight and silhouette of typical traffic, is used. Each vehicle passes several times, at different combinations of speed and load and with small variations in lateral position.
4. Full Reproducibility Conditions (R2): a large sample of vehicles (some tens to a few hundred), taken from the traffic flow as representative of it, and statically (or at low speed on an approved system) weighed, is used for the calibration.

Use of the VTT instrumented vehicle as a calibration tool

The instrumented vehicle owned and instrumented by VTT was used at the Luleå (Wave, 2001-5) and Metz (Wave, 2001-1) test sites. It is a 3-axle rigid lorry with tandem rear axles. This old vehicle has rather poor steel suspensions, which could induce substantial vehicle dynamics.

Some problems were encountered in Metz with fully synchronising the data from the vehicle with the data from the individual WIM sensors, despite the use of reflective tapes bonded to the road and detected by the vehicle. Further, the dynamic calibration of this lorry was not available. Thus only the static calibration results were used, which is not fully appropriate. Therefore, the accuracy of the instrumented vehicle data, which should be at least five times better than that of the WIM sensors in order to have a reliable reference, was not good enough to be used for calibration.

Dynamic loading patterns along the test area in Metz and Luleå were in good agreement with the road evenness (“excellent” and “good” respectively).

The test site on the A31 motorway in Metz is equipped with 18 piezo-ceramic bars of which 16 were used for the analysis and the bar spacing is 1.6 m. In order to simulate the case of poor evenness and to induce significant dynamic load variations, a bump was installed on the (closed) traffic lane for 23 vehicle runs.

The coefficients of variation (*CoV*'s) of the impact forces measured by the WIM sensors and by the VTT instrumented lorry on each sensor, were computed under full repeatability conditions. For the worst case, the *CoV*'s were:

- 4.7% for the steer axle (half load, 80 km/h),
- 7.38% for the second axle (first of the tandem) (full load, 80 km/h) and
- 8.82% for the third axle (second of the tandem) (full load, 80 km/h).

Therefore, the confidence intervals for the impact forces at a level of confidence of 95% (i.e. the repeatability of the measurement) are ±9.4% for axle 1, ±14.6% for axle 2 and ±17,6% for axle 3, if centered on the mean. The scattering of these measurements is far too high; in repeatability conditions, the maximum variation for the reference value of an axle impact force should be ±2%.

The individual calibration coefficient for a given sensor is defined as the reference impact force measured by the instrumented vehicle on this sensor, divided by the impact force measured by the sensor. Such a calibration coefficient may be related to an axle (e.g. steer axle, drive axle or rear axle) or to the gross weight. It was found with the VTT lorry that the calibration coefficients for the steer axle and the second axle of the rear tandem were greater than unity, while those for the first axle of the rear tandem were less than unity.

When the bump was placed on the road, larger dynamic loading was found and the calibration coefficients were different but not easy to analyse.

The calibration coefficients vary from 0.71 to 1.16 with a mean value of 1.04.

It has been found that the more scattered the repeatability measurement of the bar, the more influence the load has on the calibration coefficients. Further, the more scattered the repeatability measurement of the bar, the more influence the speed has on the calibration coefficients. Due to the age of the instrumented truck, its own vibrations tended to interfere with the dynamic axle load measurements when it was running at higher speeds (90 km/h). These measurements should perhaps be ignored.

Furthermore, the axle rank in the VTT truck was shown to have a great influence on the calibration coefficient.

During the CET test in Luleå, different WIM systems were tested. The results obtained will not be compared here, but rather used as examples.

It has been noted that dynamic axle loads showed a fairly high spatial repeatability. The bending plate caused a change in the dynamic axle load. For four different speeds, the small unevenness caused by the bending plate put all the dynamic axle loads in phase; this phenomenon is later dissipated. The same has been found in computer simulations. (Figure 13). The horizontal bars show the position and the length of the bending plate and the corresponding axle loads measured by the WIM system.

WIM readings fit reasonably well with the dynamic loads measured by the vehicle.

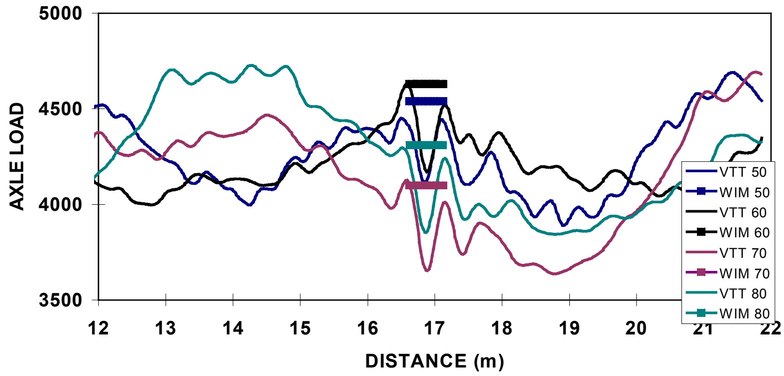


Figure 13: Dynamic axle loads of steering axle at four speeds; 50, 60, 70 and 80 km/h, and corresponding WIM-measurements

Calibration by axle rank

A number of factors influence the accuracy of static load estimation by WIM and may induce some load transfer from axle to axle, or some bias in the axle loads: the driving torque, the aerodynamic forces applied to the vehicle, tyre types (single, dual), tyre width, size of tyre imprint, tyre inflation pressure, the local pavement deflection and unevenness, sensor response and its shape with respect to time or its extension in the traffic direction.

Data collected by several WIM systems using different sensor technologies, on two different sites, were analysed. The influence of static axle load, speed, pavement temperature and axle spacing on the load estimation was analysed. If precisely known, the influence of these parameters could be corrected in real time and on-site by an automatic self-calibration procedure. Then the bias by axle rank was investigated with respect to static loads. Finally, based on the experimental findings, some bias corrections by axle rank are proposed, and applied to data samples in order to determine the accuracy improvement that are possible (Stanczyk, 1999).

The data used for this study were taken from tests performed on the Continental Motorway Test (CMT) site (Stanczyk and Jacob, 1999), and on another motorway test site used to qualify the WIM systems implemented in the National French programme "SIREDO" (Rambeau et al., 1998). The Continental Motorway Test (CMT) belongs to the European Test Programme (ETP) of the COST 323 action (de Henau and Jacob, 1998). It was carried out on the A31 motorway, in the North-East of France, at the Obrion site. The site is excellent for WIM, in class I of the European specification (COST323, 1999). Six marketed and two prototype WIM systems were installed at the Obrion site; 3 used piezo-ceramic strip bars, 2 used piezo-ceramic nude cables, 2 prototypes used piezo-polymer sensors and one used a capacitive plate. The WIM systems selected for the SIREDO WIM network had to be tested for approval and system certification. This test was carried out on the slow lane of the A75 motorway, near Saint-Flour in the centre of France, south of Clermont-Ferrand. The A75 site is also excellent - in class I according to the COST 323 specification. Three WIM systems were installed in 1996, all using piezo-ceramic strip sensors (bars).

In both tests, all the piezoceramic sensor WIM systems used an automatic self-calibration procedure.

First the effect of various parameters on the error of static load estimation was analysed. Then, the mean bias on static axle load estimation by axle rank was analysed. The influence of the following parameters was investigated: total weight, axle load, vehicle speed, temperature and axle spacing. For three other vehicle categories, the mean bias was analysed by axle rank for all the systems on both sites.

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

Analysis with the CMT data

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

The systems were insensitive to all four parameters except the speed: the higher the speed, the greater the load transfer from the steer to the drive axle. That may be due to aerodynamic and driving torque effects.

For each system, the biases by axle rank have been analysed for four vehicle categories. In most cases, the absolute values of the mean bias are smaller than the standard deviations.

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

Analysis with the SIREDO test data

On the Saint-Flour site, the biases were higher than those observed on the CMT site. Systems using the same type of sensor and the same mounting, present biases varying in the same way.

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

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

General equations to be implemented on the raw data have been written, providing two coefficients for each site.

Validation of the calibration by axle rank by simulation showed slight accuracy improvement for single axles and axles of a group. However, these results are promising because the axle rank procedure seems to be rather robust and to systematically improve the accuracy.

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

As a conclusion, the calibration by axle rank provides promising results. Systematic biases were found for many WIM systems on various sites, for some axles of the trucks weighed in motion. These biases depend on the axle ranks, and may be partially explained by phenomena related to the pavement condition, the dynamics of the vehicle and the sensor behaviour.

A calibration by axle rank can remove or reduce these biases, and thus improve the WIM accuracy for static weight and load estimation.

Conclusions

Even if the WIM systems themselves were perfect, i.e. if they could measure very accurately the axle impact forces, calibration would still be needed because of the site dependent dynamic effects induced in the vehicles, and the local traffic conditions. Therefore, it is recommended in the European Specification on WIM to carefully calibrate each newly installed WIM system (initial calibration). Then, because of pavement wear and ageing, possible changes in traffic conditions, and possible changes in the system and sensor themselves, it is recommended to perform periodical calibration checks, such as twice a year, every year, or more often, depending on the application and the required accuracy.

Any major change in the pavement or traffic condition should lead immediately to a re-calibration.

The usefulness of using empty vehicles in calibration is doubtful because the axle, and particularly the tandem or tridem may ‘jump’. Moreover, the required accuracy is generally higher for fully loaded (or even overloaded) vehicles. Thus, fully loaded and half-loaded lorries are mainly recommended. It is very important to use only air suspension lorries for calibration purposes, because it was shown that the static reference axle loads cannot be accurate with steel suspension, above all for bogies.

With the great temperature range found at Luleå (-45°C, +25°C), some WIM sensors were found to be temperature-sensitive in cold climates (Hallström 1999, WAVE 2001-4). It is highly recommended to the manufacturers to check the behaviour of their sensors in extreme temperatures if the systems are to be implemented in such a climate.

The VTT instrumented vehicle did not provide sufficiently accurate enough for calibration. It was very difficult to synchronise the on-board dynamic axle load record with the sensor readings. Moreover, this vehicle was more than 25 years old and had a poor suspension. The tyres are also narrower and smaller than those widely used by current vehicles.

The cost of the vehicle instrumentation and calibration is rather high but perhaps not excessively so if the vehicle is used for a range of applications.

The 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 may be 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. That is important for high-accuracy systems, as would be required for legal applications (Jacob and Stanczyk, 1999), but also for pavement engineering and accurate aggressivity calculations.

These preliminary results still have to be verified on a larger scale, with more test data. It is expected that, in some circumstances, one accuracy class may be gained using this procedure.

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

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

In countries where the ground freezes, pavement deformation is largely due to the effect of heavy vehicles using roads during the spring thaw. To be able to weigh vehicles in motion accurately has therefore become hugely important. One of the objectives is to determine the relation between road damage, vehicle weight and other variables that can affect the source of damage. That is why a knowledge of sensor performance in cold environments is important.

The objectives of this package included testing the capability of existing and future WIM systems to operate effectively in cold, northern and mountainous climates under harsh conditions as well as testing existing calibration procedures in cold climates. It aimed to evaluate and report the performance and durability of existing and prototype WIM systems in cold climate conditions.

3.2.1 Description of the test site in Luleå (Sweden)

It was a requirement that the climate at the chosen test site included periods with snow and frozen pavement. As the traffic density is rather low in such parts of Europe, the only possible road was E4, (European Highway 4) which is the main road connection to the northern part of Sweden and Norway. The site was located at Aleån, 20 km south of the city of Luleå in Sweden and 950 km north of Stockholm (See Figure 14). The road at the test site has two lanes and is absolutely straight for 2.5 km as it was built for use as a military airfield in the event of war. It was found to be a good site - class II - for a WIM site according to the European Specification.

Between November and May, the average temperature over a 24-hour period is normally below 0°C. During the spring season, the roadway is exposed to repeated cycles of freezing and thawing. There are extensive amounts of precipitation during this period, mostly in the form of snow. The road is ploughed and is usually free of ice, at least in the wheel tracks. Salt is spread principally at the beginning and end of this period. A road weather information system (RWIS) for the automatic collection of weather data was installed at the test site. There are great variations in the temperature at the test site in the air, but also in the pavement at two levels.

Figure 14: Aleån test site in Sweden.

According to local traffic tradition in the area, vehicles on 13- metre roads (like the one at hand) generally make use of the shoulders to facilitate being overtaken. For the purposes of the field trials, this meant having to use cones to steer vehicles onto the traffic lane.

Four systems, as shown in table 9, were installed on June 6th and 7th 1997. There was a slab bridge at the end of the test site to be used for Bridge-WIM experiments, the results of which will be presented further on in this report. It is a two-span integral bridge which is straight in plan. Traffic is carried by one lane in each direction with no central median.

Manufacturer	**Sensor type**	**System name**	**Acronym**
Pietzsch Automatisierungs-technik GmbH	Bending Plate (strain gauges)	DAW 100	PAT
Kistler/Golden River *Sensor:* **Kistler Instrumente AG** *Electronics:* **Golden River Traffic Ltd**	Quartz module	Lineas Marksmann 660	KI GR
Datainstrument AS	Piezoceramic nude cable Vibracoax, ∅ 3 mm	Datarec 410	DI
Omni Weight Control Ltd *Prototype*	Bending beam (Steel structure with a plate supported by instrumented beams, fixed on a concrete slab)		OWC

Table 9: Pavement WIM systems installed at Aleån, June 6th and 7th, 1997

On site, eight mechanical strain amplifiers were bolted to the centre of the soffit of the bridge under the southbound carriageway of the first (North) span. Pneumatic tubes were fixed across the southbound lane. The strain sensors were positioned at the same points for each test. The pneumatic axle detectors were positioned differently for each test with the second detector always being at the centre of the support between the two spans.

3.2.2 Experimentation in Luleå

System calibration

All manufacturers had been consulted in writing as to their wishes regarding the calibration. A consensus was then reached at the test site regarding the calibration runs. The following test vehicles provided by the SNRA, were used: a 3-axle truck and a 6-axle semi-trailer with tridem axle (wide base tyres in the trailer).

Each vehicle provided 5 runs at 4 different speed, which means 35 runs in total. The axle loads were measured with the portable static axle scales and the results given to the participant manufacturers.

A 3-axle instrumented vehicle provided by the VTT measured the instantaneous axle forces, which were exactly matched with the measurements made by the WIM systems. The VTT vehicle was only used in the first summer measurements in June ‘97 (3 runs at 4 different speeds).

Test plan

During 1997 and 1998, there were six short test periods, in summer ‘97, winter ‘97-‘98, and summer ‘98. The vehicles were weighed axle by axle using portable scales and a weigh-bridge to obtain the gross weights when possible.

Bridge WIM measurements

As the data collection was not automatic, the Bridge WIM system only participated when TCD staff were present, namely, in June ‘97, March ‘98 and June ‘98. In all three cases, the system was re-installed and re-calibrated. The resulting raw data was subsequently analysed independently by staff at TCD and ZAG using different Bridge WIM algorithms.

Static weighing equipment

The static reference weighing was conducted about 2 km downstream from the test site. The area was equipped with a weigh-bridge owned by the SNRA. It is calibrated and approved for weight regulation enforcement. Each individual wheel was weighed here with portable wheel load scales(See Figure 15).

Weighing vehicles on the portable scales works extremely well at temperatures above 10 degrees Celsius. At temperatures below this there is a problem that the brakes will freeze while the vehicle is waiting to be weighed which means that the brakes may be affected when the driver subsequently rolls onto the axle scales. This makes it difficult to position the vehicle correctly while the remaining torque from non- released brakes can also lead to a certain degree of erroneous measurement results.

Figure 15: Static Weighing on Aleån test site in Sweden.

Data Collection, pre and post-processing

The WIM data were systematically compared for each vehicle and axle to the static measurements, for each WIM system. WIM data were retrieved via modem from each individual system except for the Bridge WIM system. Vehicles that were clearly identified from statically post-weighed vehicles and WIM systems were classified as first category data (certain). Vehicles which were clearly matched to WIM data but the number of axles differed by one were classified as second category data (doubtful). The data which could be matched but was totally wrong, for instance number of axles differed by two or more, was classified as third category data (poor). Vehicles which were statically weighed but could not be found from the WIM data fell into the category "missing vehicle".

All WIM systems were working throughout the test period. OWC started to provide data from the 2nd test day in June 1997 due to software modifications. KI/GR could not provide data during the December 1997 test because the interface was disabled by accident.

Post-weighed data was divided into 22 vehicle types (silhouettes) to make it easier to sort out single axles, axle groups and single axles in axle groups from the data.

The BRRC prepared software for the test analysis, according to the procedure described in the European Specifications for WIM. This software called "PESAGE", in Visual Basic 5.0, allows all file layouts to be transformed into a common layout. In addition, the system files are compared to the static file, the relative values are calculated and the accuracy of the WIM system established after checking the Normality of the distribution and skipping out the outliers, if required. The software succeeded in identifying approximately 98% of the vehicles. The remaining cases were analysed manually.

When the weigh-bridge and portable wheel systems were used together for static measurement, a comparison between both static results was done. The part of the vehicle measured at once on the weigh-bridge was compared to the sum of those same axles as determined by the portable systems and the relative errors between them was calculated. If the relative error exceeded 5%, the vehicle was skipped, so that the systems are not penalised by such measurements.

Concerning B-WIM system, the data was processed independently in ZAG and TCD/UCD using different Bridge WIM algorithms. The calculated static weights were supplied to SNRA before the measured static weights were made available to ZAG and TCD/UCD. This ensured that the B-WIM algorithms could not be altered or recalibrated in the light of the measured static values.

3.2.3 Results and conclusions of the CET

Results of the post-weighed vehicles taken from the traffic flow were analysed in full reproducibility conditions (R2), and in environmental repeatability conditions (I) for each period separately and in environmental reproducibility conditions (III) for all the periods so as to cover the seasons.

Results of the test vehicles were analysed in limited reproducibility conditions (R1), full repeatability (r1) and extended repeatability (r2) for the environmental repeatability conditions (I) for each period separately, and in limited reproducibility conditions (R1) in environmental reproducibility conditions (III).

All WIM systems survived over the winter despite very harsh climatic conditions (cold temperature, winter maintenance etc). DI, OWC and PAT systems were providing data during all tests, while KI/GR could not provide data in December 1997 due to faulty software settings and thus missed 10% of the trucks over the whole year.

The prototype OWC, missed or wrongly identified a large proportion of the vehicles as the system had no position sensor. The PAT system identified 100% of the vehicles, from those 486 lorries, 23 (around 5% of the population) presented a violation code and were skipped out of the files before the analysis. A large proportion of outliers were found with this system, because of vehicles passing partially outside the relatively narrow weighing pads. Because of wide road shoulders, which are commonly used for driving, heavy vehicles may partly bypass WIM sensors. Snow and ice will also lead drivers to use different wheel paths than during the summer time.

All the systems provided consistent results for all four criteria, with generally not more than one class difference from one criterion to another. Only DI system was equipped with a self auto-calibration procedure and no system had a temperature compensation.

The temperature variations were really high. In winter the pavement's stiffness differs from its summer stiffness and some WIM sensors are therefore temperature dependent. The road profile may also change due to frost heave.

The KI/GR combined system, using piezo-quartz sensors, was quite stable throughout the year. This provided the best results and met the accuracy class C(15) during the first semester, and D+(20) during the second semester. In fact it was not far from class B(10) until January (Figure 16) and for the whole year, it easily met the class C(15).

Month after month, the accuracy of the DI system fell. The manufacturer explained that the automatic self-calibration procedure, in service throughout the year, was affected by the trucks passing partially outside the traffic lane, even between the test periods. Light vehicles were systematically over-estimated and results were biased.

The PAT system was sensitive to the temperature, and its accuracy was affected by a large bias in winter; however it recovered its initial accuracy after one year. The manufacturer developed a temperature compensation after the test.

The OWC prototype was improved during the test by modifications of the software. The system gained approximately 20% in accuracy after one year. The poor results during the winter are due to the first modifications which were inadequate and the system also had problems to identify vehicles during winter tests. Because the sensors are installed under the asphalt layer it has a high temperature dependency. Therefore, results from the winter period are clearly underestimated. After the cold season, the results were reasonable again. A proper temperature compensation would likely improve the performance.

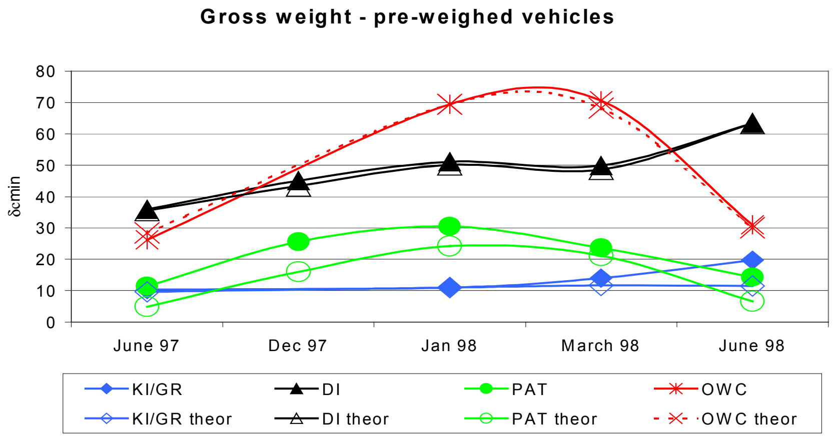


Figure 16: Accuracy class for gross weight by system and period, for the post-weighed vehicle population, before and after outlier elimination (R2 - I).

The B-WIM system was found to be in accuracy class C(15) after the first summer test and the winter test. For the second summer test, the system was in the accuracy class B(10). Finally, in full environmental reproducibility conditions (III) over the whole year, the accuracy class B(10) was achieved. However, when combining the results from the three test periods, it should be borne in mind that the system was recalibrated prior to each test, unlike the other WIM systems.

3.2.4 Tests in Switzerland

A large test was carried out at Hagenholz (near Zurich) with five WIM systems in 1993-5 (Caprez et al., 2000). In addition, in 1995, two WIM systems were installed by the Swiss Highway's Office (ASTRA, OFROU) together with the Swiss Federal Institute of Technology (ETH), in important traffic axes through Switzerland (Alpine transit routes). The first was installed at the entrance to the Gotthard Tunnel (Golden River), the second on the San Bernardino motorway (PAT).

A Golden River system was installed at the Gotthard site in June 1995. Four capacitive WIM strips (weighing sensors) and two inductive loops were installed in each direction inside the northern tunnel entrance near Göschenen, at 1100 m above sea level. Each sensor records either the left or the right wheel of a vehicle. The data logger was a Marksman 660. In summer, the average temperature is 13°C and in winter -3°C. There is snow for 4 months per year and the road outside the tunnel has to be salted. Because of the tunnel, the concentration of harmful substance causing corrosion is very high because of the water the vehicles bring into the tunnel that is not washed away by rain.

At the San Bernardino site, two 1.75 x 0.5 m bending plates manufactured by PAT and four inductive loops were installed in the Plazzas tunnel in June 1996 within two days. This tunnel is 300 m long and is located near Bonaduz, 660 m above sea level. The data logger was a DAW 100. The average temperature is + 16°C in the summer and -1°C in the winter. In winter the road is heavily salted, and the concentration of corrosive substances is very high.

Calibration checks were done every year from 1996 to 1998. In this period, both systems were working with only very few interruptions. During each check, 40 to 70 trucks were selected in each direction and lane out of the heavy traffic flow. The static weights and the geometry were measured and compared with the WIM measurements collected from the systems.

3.2.5 Results of the tests in Switzerland

After the test of 1996, the Golden River capacitive sensors failed. In 1998, they were replaced with piezoquartz sensors by Kistler, and the system was moved forward as it was installed, initially, in a curve in the southbound lane.

The test results are given in table 10. The Golden River system accuracy was affected in 1996 by the curvature of the road in the southbound lane. Otherwise, the systems gave consistent results. The Kistler/GR system in 1998 on the St Gotthard South lane was affected by a mean bias of 7.3%. The PAT system survived the salt and corrosive substances used during the four months of the wintertime over three years.

Since October 1995 the WIM systems worked with very few interruptions. In 1997 the capacitive strips by Golden River had to be adjusted and during two months the traffic was not registered. Every year the accuracy class of the PAT system was in class C(15) in the southern direction, and the class B(10) was mostly met in the northern direction. However, sometimes the mean bias was higher than the standard deviation and then the accuracy class became C(15). The Golden River system was in class C(15) in one direction and in class E(30) in the opposite direction in 1996, because the installation in the northern direction was close to a curve.

Site	Year	Company	Sensor(s)	Electronics	Cond*	Acc. Class
St Gotthard N	96	Golden River	4 capacitive strips	Marksman 660	I	C(15)
St Gotthard S	96	Golden River	4 capacitive strips	Marksman 660	I	E(30)
St Gotthard N	98	Kistler/GR	2 piezoquartz strips	Marksman 660	I	C(15)
St Gotthard S	98	Kistler/GR	2 piezoquartz strips	Marksman 660	I	D+(20)
San Bernardino N	96/97/98	PAT	2 bending plates	DAW 100	I	C/B/B
San Bernardino N	96-98	PAT	2 bending plates	DAW 100	II	B(10)
San Bernardino S	96/97/98	PAT	2 bending plates	DAW 100	I	C/C/C
San Bernardino S	96-98	PAT	2 bending plates	DAW 100	II	C(15)

* Environmental repeatability (I), limited reproducibility (II) test conditions.

Table 10: Results of the Swiss Alpine tests, (I/II-R2) - sites: Gotthard class I, S. Bernardino class II.

3.3 New technologies (WP 1.2 and WP 4)

Two new WIM technologies have been developed during the WAVE project: research was carried out on Bridge-WIM systems, which consists in using the bridge as a large scales to weigh the vehicles passing on it, and on optical fibre sensors, developed by the Alcatel company in partnership with the LCPC.

Those new technologies were both shown to have promise as accurate and durable WIM systems.

3.3.1 Bridge – WIM (B-WIM)

The B-WIM concept was introduced in the USA in the late 1970's by Moses, and initially implemented on multiple girder and simply supported medium span bridges. Subsequently, B-WIM systems were used on culverts, in a system called "Culway" in Australia. The studies carried out in WAVE aimed to improve B-WIM algorithms in order to increase the accuracy of systems, and also to extend their applicability to other types of bridge. The range of bridge types tested included short slabs (Znidaric et al., 1999), 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 (Dempsey et al., 1999). Subsequently, the 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 (Gonzalez et al., 1999) and calibration. During WAVE, these problems were shown to be readily surmountable and very high accuracy was achieved in B-WIM systems with outstanding durability.

The dynamics of the lorry crossing event

Tests were carried out on the Belleville bridge in France to develop an improved understanding of vehicle and bridge dynamics and the interaction between them. (Figure 17).

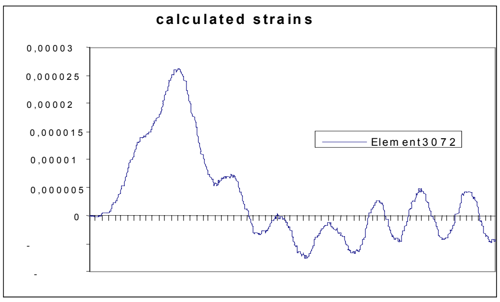
Figure 17: Belleville Bridge

Analysis of road roughness showed that amplitudes of the roughness prior to the bridge are often higher than on the bridge (typical behaviour), and that a sharp bump was commonplace at the beginning of the bridge near the joint. The exception to this is in integral construction, commonly used in Scandanavia, where there are no surface joints.

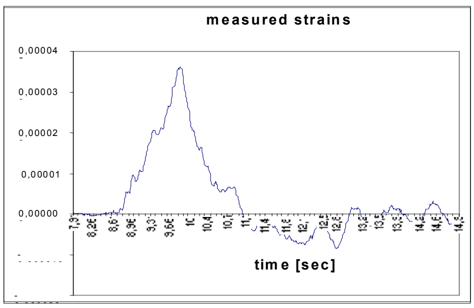
The road profile is the main source of excitation for trucks dynamics. The best sensor locations are therefore those with the smoothest road prior to and on the bridge.

A Finite Element (FE) model was developed for the bridge, and for the truck (Figure 18) (Lutzenberger and Baumgaertner, 1999).

After measurements, it was shown that the eigenfrequencies of the bridge model were in accordance with those measured on the bridge.



(a) Simulation



(b) Measured

Figure 18: Strains at Belleville Bridge

Development of a prototype B-WIM software

SiWIM© is a new WIM program, which was developed by ZAG for use with any type of bridge and which can be used with a range of alternative weight calculation algorithms. The four parts of the SiWIM software are:

- Data acquisition
- Gathering data, filtering and monitoring
- Vehicle detection
- Calculating weights

The sampling rate for data acquisition is variable within the range, 32 to 2048 samples per second.

Data is buffered between any two parts of the software, so that any delay in later stages of processing does not cause data loss.

Data can be saved at various stages of processing to enable off-line processing. Currently SiWIM© can write and read:

- filtered signals in binary ACQ format compatible with other data acquisition software in use at ZAG,
- processed strain signals in capture files with extension CAP, containing vehicle axle distances and speeds and strain transducer signals and compatible with the BWS (Bridge Weighing Systems Inc.) system,
- FHWA (US Federal Highway Administration) CD7 files, containing vehicle by vehicle information on time of weighing, vehicle category, axle spacing, axle and gross weights etc..

Signals can be filtered in real time. Filters include moving average, high-pass, low-pass and other FFT-based filters. Signals, raw or filtered, can be monitored in real time, as can power spectra of signals.

After using Moses' algorithm for obtaining axle weights, SiWIM© can pass the results to an optimisation algorithm which can, in some cases, significantly increase the accuracy of results. In addition to using the internal algorithm, SiWIM© can be used as a front-end to an external weighing algorithm via a standardised file-based interface. SiWIM© is being rewritten to reflect knowledge acquired while testing the prototype.

New approaches and algorithms

Optimisation algorithm

Steel bridges are sensitive to fatigue damage, and the repair costs of orthotropic bridges are very high. B-WIM systems can be used to assess loading on this type of bridge in order to prevent fatigue or to forecast the need for strengthening in sufficient time.

Utilisation of a Free of Axle Detector (FAD) algorithm would completely eliminate all actions on the pavement and hence increase operator safety and reduce the costs of installation and inconvenience to road users. It would also increase the durability of the systems, especially in harsh climates – durability is no longer an issue in a B-WIM system with nothing on the road surface. That is why a FAD algorithm was developed in which the velocity, number of axles and axle spacing are all determined from the strain gauges underneath the bridge (Dempsey et al., 1999).

The accuracy of the calculated axle spacing and velocity tends not to be as high in FAD systems as the more traditional methods (i.e. axle detectors on road surface). This led to a search for a new algorithm based on optimisation techniques, which would be insensitive to errors in velocities and axle spacing.

The WIM problem can then be defined as the optimisation of an objective function, which is the sum of squares of differences between the measured bending moments and the expected (modelled) bending moments, in order to determine the truck parameters, that is:

Minimise:

$$O(y) = \sum_{x=1}^{K} [M(x) - M^M(x)]^2 \qquad (16)$$

to find

$$\{y\}=\{ v, L_1, L_2,....L_{n-1}, z, A_1, A_2,.....A_n\} \qquad (17)$$

where $O(y)$ is the objective function, x is the distance of the first axle from some specified reference position on the bridge, K is the number of recorded strains during the passage of the truck, $M(x)$ is the calculated moment (obtained from the model) at an instrumented section when the first axle of the truck is at position x, $M^M(x)$ is the corresponding measured moment, v is the velocity of the vehicle, L_1, L_2, and L_{n-1} are the axle spacings between the first and second, second and third and n-1th and n^{th} axles respectively, z is a distance parameter which relates the position of the measured and theoretical response of the truck to each other and A_1, A_2 and A_n are the weights of the first, second and n^{th} axles respectively.

In any optimisation problem, initial values of the optimisation parameters are needed. If the initial values are poor, convergence can be slow and indeed, when initial values are sufficiently far from the true result, convergence cannot even be guaranteed. For this reason, a two-stage process was adopted: (i) an *identification* algorithm was used to classify the truck using simple concepts such as peak-to-peak distances in strain responses, (ii) an *optimisation* algorithm was used to determine more accurate values using output from the identification algorithm as the initial values.

Having completed theoretical and experimental studies, the following guidelines were proposed for the WIM algorithm for orthotropic bridges:

- the number of axles was calculated from the *identification* algorithm and this determined the number of parameters for the optimisation process, i.e., the objective function formula is determined,
- the initial values for the axle spacing and velocity were calculated in the *identification* algorithm, and are used as input into the *optimisation* algorithm,
- the initial weight of the axles was shown not to be critical. The initial value for each axle weight is chosen to be 30kN,
- the only constraint that is used in the optimisation is that the velocity is not allowed to vary greater than ±5% from the initial value. If the velocity exceeds these limits then a penalty function is applied to the objective function, which dramatically increases the value of the objective function and thus prevents the optimisation process from searching further in this area. That is why the initial values for the optimisation process were generated: the velocity was determined from the *identification* algorithm to an accuracy of within ±5%.

Experiments were carried out on the Autreville bridge, on the A31 motorway in Eastern France, between Metz and Nancy on the Moselle river, near the Obrion test site. This multi-span orthotropic deck steel bridge carries four lanes of the motorway. Longitudinally stiffened steel plate spans between transverse beams. These in turn are carried by very large longitudinal steel beams that traverse the river in three spans.

The tests at Autreville showed that there is inaccuracy in calculated axle weight because of variations in transverse position of trucks. To overcome this problem, an algorithm based on a two-dimensional bridge model was developed. The Finite Element model uses an influence line for each of the longitudinal stiffeners (instead of one influence line for the complete bridge as in traditional B-WIM). Then the optimisation approach allows the axle weight and other parameters to be found, with an objective function defined as the sum of squares of differences between *individual* measurements and corresponding model results.

To conclude, reducing required accuracy or completely removing the need for axle detection is very important for installation and maintenance. Furthermore, the optimisation approach to determine better fits between measured and modelled strains improves accuracy of B-WIM systems. It allows for a calibration of B-WIM systems using pre-weighed lorries without any requirement for an understanding of bridge behaviour.

Multiple equation static B-WIM algorithm

Another theoretical approach to B-WIM was to use multiple sensor locations longitudinally on the bridge, modelled using a static algorithm. Instantaneous calculation of axle and gross weights is shown to be theoretically possible for 2-axle trucks in single-span bridges and for 3-axle trucks in two-span bridges (Gonzalez et al., 1999).

The principle of the method is minimising the objective function associated with the influence line. 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. Indeed, for single span bridges and two sensor locations, both axles have to be between the two sensor locations to give two independent equations. For single span bridges and three sensors, there are three equations but one is not independent, that means that only 2 axle weights can be calculated.

For a two-span bridge and five sensors, there are two or three independent equations (depending on the location), which means that it is possible to weigh three-axle trucks, if the sensors are well located. A preliminary experimental verification was carried out on the Belleville bridge on the A31 motorway in Eastern France between Metz and Nancy. Unfortunately, there were a number of sources of inaccuracy (axles detectors were malfunctioning). Nevertheless, the multiple equation system was shown to be more accurate than the conventional B-WIM system (Figure 19).

Moreover, better results can be expected using a more suitable bridge than Belleville.

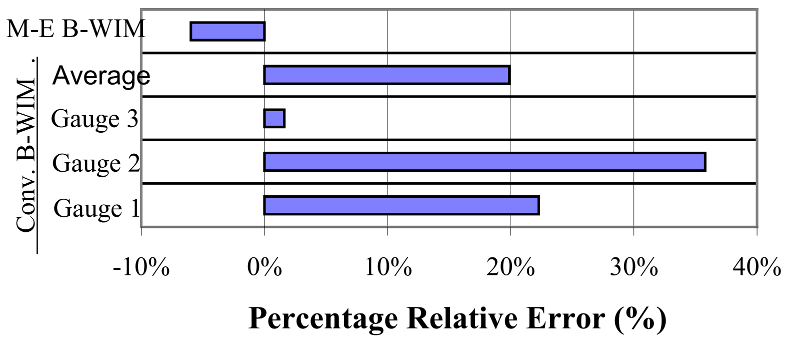


Figure 19: Comparison of results from multiple-equation (M-E) B-WIM and conventional B-WIM algorithms.

Combined B-WIM and pavement WIM system

One potential advantage of a combined Bridge and Pavement WIM system is ‘robustness’, i.e., insensitivity of the results to minor errors in the input data. It was shown that shorter bridges may give a more robust algorithm than longer ones, although this has not been verified by experiment.

A combined B-WIM algorithm is one which combines data from a pavement WIM system with strain data taken from a simple B-WIM system. The objective is to increase the accuracy the overall result. The combined bridge weigh in motion system works in much the same manner as the standard B-WIM algorithm except that it uses additional information obtained from the pavement sensors in the form of estimates of instantaneous dynamic axle weights.

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) (systems individually gave class B(10)).

The development of a dynamic bridge WIM algorithm

This part of the research has focused on alternative algorithms based on modelling the dynamic behaviour of the bridge-truck system. One of these algorithms is based on a frequency spectrum approach, where a knowledge of the influence line not required. This system is calibrated in a totally experimental way.

The spectral approach uses the frequency components of the strain signal. The spectrum of the bridge response to a calibration truck is calculated. The spectra is limited by the time the load is on the bridge and low frequencies components could not be defined accurately in every case. Accordingly, while effective for vehicles with a low number of axles, this frequency domain approach failed to accurately predict the weights of a high number of axles.

An alternative dynamic approach is the *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.

It is obtained by (a) experimental determination of the natural frequencies and damping of the bridge, (b) calculation of the mode shapes based on the bridge geometry, (c) adjustment of the unit response curves to give a best fit to the static values of the calibration vehicle.

The theoretical model is also generated with constant loads, so interaction between bridge and truck is neglected. This simplification allows a calculation in real time.

The total measured strain and the real static strain are obtained from numerical simulations. The dynamic adjustment is much closer to the measured strain than the static adjustment. The multiple sensor systems are not able to reproduce the instantaneous applied axle force accurately, but the dynamic system gives results around the real static weight along most of the bridge length.

A dynamic bridge WIM algorithm (DB-WIM) based on one sensor location was then developed. The formulation for DB-WIM algorithm is derived by minimising an error function defined by the squares difference between measured and theoretical strains. The difference from SiWIM© approach would be the use of the dynamic response due to a unit load instead of the influence line.

Truck dynamics are removed through least squares fitting of all the readings along the bridge. The value that is obtained should be very close to the static answer but was not tested.

Anyway, 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.

Durability: Free of Axle Detector systems (FAD)

Following the success in developing a FAD system for orthotropic bridges, it was decided to extend the same principles to other bridge types. Not all the bridge types are appropriate for FAD systems. Indeed, shorter spans have several advantages over longer spans (identification of each axle contribution is possible and leads to improved accuracy).

The general shape of the strain signals under the moving vehicle is defined by different parameters as: the shape of the influence line, the ratio between the span length and the (short) axle spacing, and the thickness of the instrumented superstructure (influences 'sharpness' of the bridge response).

A FAD coefficient is defined as:

$$FAD = \frac{L \times h}{d_{\min} \times f_i} \tag{18}$$

where L is the length of a span, H thickness of the superstructure, d_{min} minimal axle spacing and f_i a factor related to the influence line.

A span is appropriate for the FAD algorithm if the FAD coefficient is lower than 2.

Good candidates for FAD B-WIM instrumentation are:

- short span, frame-type slab bridges with an f_i factor of around 3 and a FAD coefficient of between 1 and 2,
- longer span bridges with a thin slab which is supported in the lateral direction by cross beams or stiffeners (orthotropic deck or similar) with a FAD coefficient below 0.5. (Figure 20).

Figure 20: Two types of slab bridge instrumented for bridge WIM

In the FAD algorithm, velocity and axle spacing are first estimated from the peak-to-peak time difference between axle strain responses. They are subsequently calculated more accurately by optimisation. The procedure overall consists of:

- applying an *identification* algorithm to classify the vehicle and estimate velocity and axle spacing (more efficient for orthotropic decks),
- applying the same algorithm as some B-WIM systems with axle detectors. This algorithm finds the axle weights and more accurate values for velocity and axle spacing. It achieves this by optimising to minimise the sum of squares of differences between measured and theoretical strains.

For orthotropic decks, FAD was shown to work consistently. For other bridge types, the range of applicability of the method was determined. It is anticipated that the method will be extended in the future to a wider range of bridge types.

The SiWIM© software had to be upgraded for FAD application. To provide automatic real time axle detection based on measured strain signals from short slab bridges, a new module for the SiWIM© software is under development. As in the orthotropic deck algorithm, it searches for axles by permanently monitoring the amplitude of the strain signal at every point.

Testing the accuracy of B-WIM Systems

Orthotropic bridge WIM

The Autreville bridge was used to test the prototype B-WIM system for orthotropic decks. (Figure 21).

Figure 21: Autreville bridge in eastern France

At Autreville, the FAD algorithm identified 63 trucks out of 64. (the 64th was identified once the algorithm was extended to allow for 6-axle trucks).

The output velocity, axle spacing, axle and gross weights were compared to the results of traditional methods. The accuracy of the calculated velocity was found to be within a tolerance of ±5%. The errors in the axle spacings determined by the *identification* algorithm were found to be sufficiently small to guarantee convergence of the *optimisation* algorithm.

The accuracy class obtained for each category was found to be D+(20).

As transverse location of the truck affects the amplitude of the bridge response, a new optimisation algorithm based on a two-dimensional bridge model was developed. This resulted in an improvement in the accuracy class to C(15).

Tests in Luleå, Sweden

The bridge selected for instrumentation was a two-span integral bridge. The data was processed independently in ZAG and TCD/UCD using different B-WIM algorithms. The algorithm developed by ZAG is known as SiWIM© while that developed in TCD and UCD will be referred as DuWIM.

DuWIM achieved an accuracy class of B(10) without alteration, while SiWIM© could reach B(10) after adjustment.

Slab bridges

Several different types of short slab bridge were instrumented. They are the most common bridges in many European countries and are usually easy to instrument. The SiWIM© software was used for the analyses.

The first instrumented type of short slab bridge was an integral slab bridge. Unfortunately, only one of four channels was properly amplified and results were calculated from strains from one transducer only.

Different types of analysis comprise:
- Theoretical influence line for single fixed supported span was used, calibration factor for all vehicles was obtained from the first five 5-axle semi-trailers. This led to an accuracy class of D(25);
- As above except the theoretical line was replaced with the experimental one: D+(20);
- As above but 2 calibrations factors were used (semi-trailers / all the rest): C(15);
- Optimisation of results (minimisation of error) to adjust velocity and to fine-tune the axle loads: C(15).
- In addition, for all vehicles except for 2-axle trucks, 4% of load from the first axle was redistributed to all other axles: B(10).

An experiment was also carried out on two-span integral slab bridges, skewed at 7° and 26°. The study of the influence of skew on accuracy showed that the straight bridge had an accuracy class C(15), while the skewed bridge was in D+(20) (just slightly lower). This result implies that carefully instrumented and calibrated skewed bridges can provide satisfactory results.

The influence of surface roughness and evenness was also studied for integral slab bridges with a span of 8m and a bump. Gross Vehicle Weight (GVW) remains very good, but there is a considerable redistribution of light single axles and axle groups. The accuracy class was found to be E(40) but, if all axles below 20kN are not taken into account (as allowed by the European Specification COST 323), accuracy increases to C(15).

The bridge chosen to represent the culvert type of construction was not suitable for FAD (Free of Axle Detector), but it obtained class D+(20) with a conventional B-WIM installation.

In conclusion, a typical integral slab bridge with average evenness of the pavement showed that careful selection of the influence line and higher methods of calibration can result in an overall accuracy class of B(10). The majority of short span slab bridges, which are easy to find and instrument, can be used for B-WIM measurements.

Conclusions, recommendations and future needs

Bridges instrumented for weigh-in-motion measurements are still quite rare around Europe, despite being well represented in Australia (over 100 Culway systems) and in some other countries. As bridge spans are much longer than pavement WIM sensors, they have considerable potential for high accuracy. In addition, the same strain records can be used for bridge monitoring and as indicators of structural damage by fatigue. Research reveals that major difficulties observed with B-WIM systems in the past (limited selection of appropriate bridges, lower accuracy of results than expected etc.) can be avoided when using new and updated algorithms and more powerful computers and data-acquisition systems. The accuracy of the recent results is most encouraging; B-WIM systems have been shown to have accuracy easily comparable to other types of WIM system.

In addition, several advantages of B-WIM systems have been identified or confirmed. Firstly, B-WIM systems require limited activity on the pavement. This greatly improves the durability of the equipment and increases safety and reduces traffic delays during installation and maintenance. This is of particular importance in cold climates. Also, first successful attempts have been made on some bridges to replace the axle detectors with appropriate strain readings from under the structure. When fully developed, this should further improve the durability of B-WIM systems. Secondly, installation of a B-WIM system is fast, easy and the system is completely portable. Thirdly, off-scale weighing is eliminated as B-WIM systems weigh the complete vehicle. Lastly, the evenness of the pavement has less influence on the accuracy of weighing than with pavement WIM systems.

On the other hand, some difficulties have not been entirely solved yet. One of them is the presence of more than one heavy vehicle on the bridge at the time of weighing which, at the moment, induces higher errors than when vehicles are present individually. However, if short bridges are instrumented, the probability of such events is very low. The second one is that, despite a greatly extended selection of bridges, some road sections may still not have an appropriate bridge for B-WIM measurements.

It seems likely that further progress will be made in B-WIM on several fronts. The developments in FAD - Free of Axle Detector systems - are most promising and will provide a very strong reason for using B-WIM in preference to pavement WIM in some circumstances. These are in their infancy and there are many potential improvements in accuracy and in the range of bridge types that can be utilised. It seems inevitable that FAD will be accompanied by the widespread adoption of optimisation techniques as pioneered for orthotropic B-WIM. This will eventually overcome the reductions in accuracy that might be anticipated with FAD. Other methods to improve accuracy will emerge which may involve dynamic algorithms and/or combinations of bridge and pavement WIM for the first class A accuracy systems. It seems beyond doubt that the future prospects for B-WIM are bright indeed.

3.3.2 Fibre Optic WIM systems

The development of fibre optic WIM systems is mainly supported by a private industrial company (Alcatel CIT), in partnership with LCPC (Caussignac and Rougier, 1999). 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. That was the objective of the WP4 in WAVE (WAVE 2001-6). This work will lead to the development and manufacture of a relevant European WIM 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 during the project, as well as the required software, and the device was designed to allow it to be inserted into a 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.

Principle of measurement

The WIM sensor is built with optical fibres; the measurement principle uses light birefringence in optical fibre induced by mechanical strain. Indeed, some transparent materials like fused silica have the property to become birefringent under external actions. Then, two waves can propagate independently with different polarisation. If one polarisation direction is selected at the fibre end by a linear polariser, the transmitting light intensity varies as the birefringence moves, resulting in a fading phenomenon. This is referred to as polarimetric fringes in optical systems because of the successive minima and maxima in light intensity.

Let n and λ be the refractive index and the operating wavelength of the optical fibre of length l. Then, the birefringence property states that the refractive index fluctuates by an amount Δn, which depends on the principal stress difference (X and Y axis) as follows:

$$\Delta n = \frac{(1+\nu)(P_{11} - P_{12})}{2E} n^3 \left(\sigma_X - \sigma_Y\right) \tag{19}$$

where the mechanical characteristics of the optical fibre are: E the Young modulus, ν the Poisson ratio, P_{11} and P_{12} the photo-elastic constants.

When a linearly polarised light comes into the fibre, the birefringence results in a fluctuating intensity (fading) which is caused by the phase shift between the two characteristic polarisation phases. The phase shift Φ by unit length is given by Equation 20:

$$\frac{\Phi}{l} = \frac{2\pi}{\lambda} \Delta n \tag{20}$$

The sensor uses the photo-elastic effect in glass: a vertical compressive force applied to glass changes light velocity in optical guide, because of the refractive index moving. This induces the separation of two propagating modes: the faster mode (vertical) and the lower mode (horizontal). The incident light, Ei, is linearly polarised in a plane at 45° angle to the horizontal plane. At the fibre end, after light propagating along length L, a delay is induced between the two modes and creates a phase shift Φ between the two transmitted waves:

$$\Phi/L = 2\pi.\Delta n/\lambda \tag{21}$$

An optical receiver connected at the sensor end will sum up the two modes, and a photo-diode transducer converts light power into an electric current I_t. After travelling through the sensitive optical fibre, light is coming back towards the receiver by a non-sensitive fibre placed inside the same bar. Therefore, the sensor only needs one connecting wire to operate.

In order to measure a strain or stress, a single mode optical fibre is placed between two metal ribbons connected together along the two edges. Bending the ribbons induces a compressive force in the fibre. Under these conditions, the force to be measured is only applied to the vertical axis of the fibre. Thus, the light has a constant velocity along the horizontal axis and a variable velocity along the vertical axis.

A coherent, linearly polarised light beam is inserted into the fibre at a 45° angle with respect to the vertical axis. The light beam travels along the fibre with two different velocities, as explained above, such that, at the end of the fibre, a delay is observed between the two modes, or a rotation of the received light polarisation. To detect phase variations, an analyser is placed in front of the receiver, which selects one polarising direction. In these conditions, light intensity minima and maxima alternate as a function of the load applied to the sensor. The period corresponds to a 2π phase-shift. An example of given fringes is showed (Figure 22).

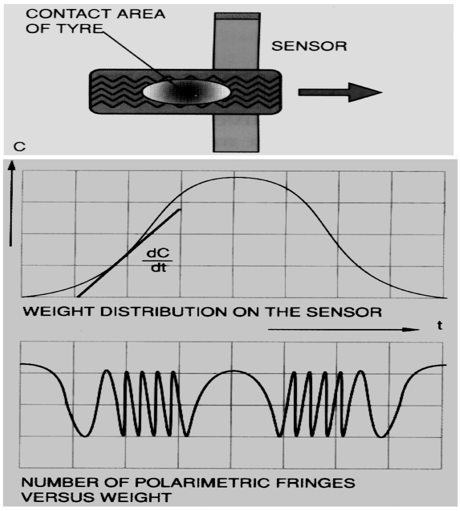


Figure 22: Example of typical signal from optical fibre sensor

Simple fringe counting is used to determine the change in birefringence, relating to the weight of one wheel. A typical vehicle signature is characterised by a number of fringes *M*, which depends on the weight, the crossing time *T* (versus speed), and the tyre pressure. Whatever the pressure tyre, the number of fringes is the same, even if the signature varies.

When a vehicle passes over the sensor the signature is interpreted as follows:
- first fringe shift corresponds to increasing load as tyre rolls on the sensor,
- continuous signal indicates quasi-static pressure while tyre is centred on the sensor,
- second fringe shift corresponds to decreasing load as tyre rolls off of the sensor.

The total vehicle dynamic load is calculated as the sum of individual wheel weights. The signal has to be processed after being recorded. Operational acquisition requires an optimum choice of triggering conditions, sampling frequency f_S, record duration, and data processing architecture. These parameters must be selected according to the vehicle parameters (above all speed range and axle load). This, in turn, determines the acquisition strategy and processing hardware to be used.

The instantaneous phase shift $\Delta\Phi(t)$, as measured by the sensor, is proportional to the instantaneous load $P(t)$:

$$[\Delta\Phi(\tau)]/2\pi = K.P(t) \quad (22)$$

where K is a constant (in cycle/kg), typically 0.083 and 0.167 for current sensors, which means 12 and 6 kg/cycle. The constant value for each sensor is determined by calibration. The observed signal is expressed by:

$$y(t) = A + B\cos(\Delta\Phi(t)) \quad (23)$$

which corresponds to a fringe frequency of:

$$f_{\phi}(t) = [1/2\pi][d\Delta\Phi/dt] = K\,[dP/dt] \quad (24)$$

Coefficients A and B in (23) are also assumed to be known, and are continuously updated in an adaptive way during processing. They are deduced from the extreme values, $(A + B)$ and $(A - B)$ of the signal.

Acquisition conditions - and in particular sampling frequency fs - depend on the maximum fringe frequency, and thus is related to load variation stiffness. Such rates prohibit acquisition and processing for load reconstruction to be made in real time on a Personal Computer (PC). For real time processing, dedicated hardware has been designed, and is currently being developed. A single mode evanescent field coupler is used to produce a $\pi/2$ phase delay on one polarisation direction. After recombining and detecting, this is used to generate another observed signal. From there, simultaneous checking of cosine, sine, and sign of sine allows removal of phase ambiguity and phase extraction. Data from one wheel sensor crossing is kept in a circular buffer, and transmitted to a PC station through a serial link. All operations are managed by a micro-controller.

Equipment description

Before making the equipment, the theoretical sensor design and behaviour were tested by simulation under loading. These models were validated by experiment both in the laboratory and on site.

Studies were carried out by the LCPC to develop a model of the sensor with Finite Element methods in order to optimise the design and to simulate its metrological behaviour under various environmental conditions. Alcatel chose and tested optical and optoelectronic components, and improved the design of the electronic card performing real time numerical processing. Simplification was made to manufacture the device, and AML (Applications Mathématiques et Logiciels), sub-contractor of Alcatel, performed mathematical studies to develop data acquisition and processing software.

The sensing ribbon is made of a single mode optical fibre squeezed between two metal strips welded together by a crimping technique. The optical guide is preloaded with a compressive force due to metal strip elasticity. The design allows forces to be received and to be summed up them at two points of a fibre diameter, in a constant vertical plane all along the sensor (Figure 23). The sensitive ribbon is placed within a composite U profile, filled with an elastomer material. The bar is 3.7m in length; an optical wire is connected at one end. On site the sensor is placed flush with road surface. A groove is cut in asphalt. Sensor is laid down and fixed by an epoxy resin mixed with sand.

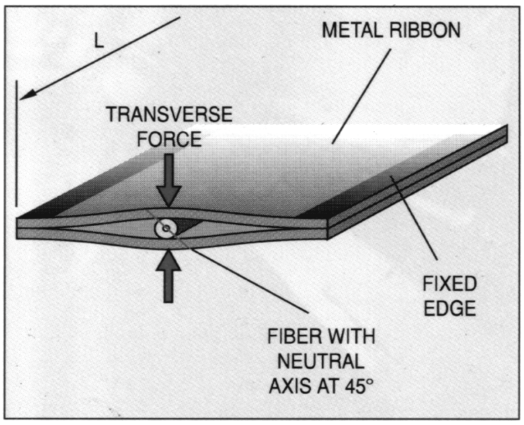


Figure 23: Sensitive element of the sensor

The sensor design was deduced from modelling by Finite Element method. The geometry of components and material characteristics were defined and the sensor behaviour studied under various conditions in order to choose the best characteristics.

The optoelectronic head includes a 1330 nm laser with its driver, two photodiodes with two electronic amplifiers, an optical coupler, and two light polarisation filters. The four electronic signals given by the optoelectronic head are connected to a data acquisition module which digitises these signals at a 10/250 kHz rate, with a 12 bit resolution. Data is then recorded in a hard disk of a portable computer which enables measurements to be recorded, weights computed and speeds, and to show signals and results. One single optoelectronic head is able to manage two sensors. Extension to multiple sensor WIM is possible.

The optical link between each sensor and the optoelectronic head may reach up to one or two kilometres. An option was developed which allows it to be connected with communication optical fibres generally located along roads to transmit various data.

AML developed an adapted software. This software reads two measurement series, sine and cosine, for each sensor, and identifies the beginning and the end of each wheel; then, it computes the phase of the optical signal coming out of the sensor. Using data from two sensors, the software calculates the wheel speed, the force applied by the wheel to the ground, the distance between two wheels, and the vehicle weight. Then the software writes results in an output file, and displays the results.

Sensor characterisation

All sensors are calibrated in the laboratory under a pressure machine, before installation into the road. Calibration aims to check the spatial homogeneity of the sensor response and its metrological performance: range, accuracy, resolution, etc.. To carry out tests, various forces are applied by an incremental procedure to a sensor limited zone. All measurements are repeated along the length of the sensor. Sensor response has been normalised to be able to perform comparisons between several sensors and various sensitive areas for one sensor. N/cycle is the unit used.

It was found that the accuracy depends on the loading level. This can be explained because, for low loads, the fibre delivers a few polarimetric fringes. Thus, the relative error on the weight calculation is higher. A normal sampling rate of at least four readings per fringe enables the resolution to be increased by a factor two. For low loads, the sensitivity is better than 10%, while for higher loads, it becomes better than 7.5 %. The mean testing loads were chosen in the range of a force induced by a heavy truck axle.

A second experiment was carried out to test the repeatability of the sensor response. Three load levels were considered and five limited areas along the sensor were selected out of thirty, to apply the loading. The testing sequence was repeated 10 times.

It has been shown that quality improvement between the first and last generation of sensors allowed the best spatial homogeneity of the sensor response to be found.

Tests and Experimental Results

Before the project, in December 1995, two sensors were laid on the RN10 site near Trappes (France). The traffic flow is about 10,000 vehicles a day, among them 20 to 25% of lorries. The two sensors have kept their initial performances and a satisfactory behaviour under heavy traffic and various weather conditions for two years. That confirms the choice of the sensor design. An epoxy resin is used to fix the sensor within the pavement, which constitutes a good compromise between the metrological performance and the long term durability of the sensor.

Two parallel 3.7 m optical sensors, 1.5m spaced, and a 1.5 m sensor from a new generation were tested on a parking lot in the Alcatel plant in Saintes by November 1998. They were mounted in a concrete slab built as a pavement section. This experiment was also used to test the acquisition system and to develop the processing software. Each sensor is linked to an optoelectronic head, which monitor two optical fibres.

The two observed periodic functions on the same graph (Figure 24) show signals given by two optical receivers linked to the sensor output according to two polarisation directions. The bar curve provides the instantaneous strength reconstruction received by the sensor. The impact force curve provides a greater wealth of information than results given by other sensor technologies. Figure 24 shows the tiny ground motion before and after the wheel runs over the sensor.

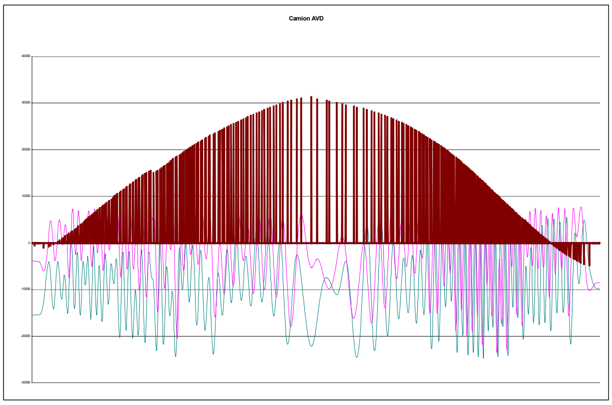


Figure 24: A truck wheel – load reconstruction

Measurements were carried out with vehicles at speeds between 10 and 15 km/h. The results are shown in Figure 25. The Y axis indicates the ratio of measured impact force/ static weight. The X axis indicates the static weight of the wheel.

During the calibration procedure, a large scattering of the results was observed. The main cause was the degradation of the concrete slab surface. At the end of the winter, level differences reached ±15 mm, which caused random motions of vehicle suspension. The scattering was then reduced by checking more accurately the location of the tyre imprint on the sensors. The poor quality of the pavement affected the apparent accuracy of sensors.

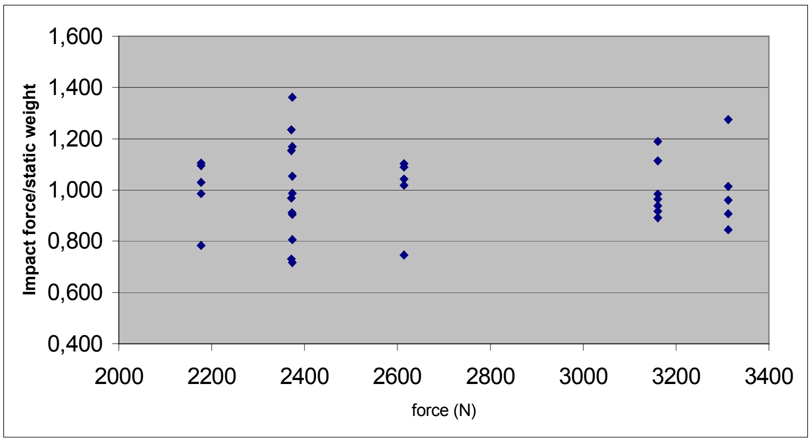


Figure 25: Comparison between impact force and static weight for a given force

It was found that resolution does not depend on the total load. This resolution of 30N 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.

Main Features of an Optical Fibre WIM system and Conclusions

Finally the main characteristics of the WIM system using the optical fibre technique may be assessed as follows.

First, 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..

The optical sensor technology was improved during the project: sensor shape, fixing elastomer, manufacturing process, and testing methods. A reliable optoelectronic converter, well suited to the sensor requirements, has been achieved. Processing principles were studied with the help of the AML company. The processing software was implemented and tested.

Preliminary results, found in the laboratory, showed that the sensor sensitivity was 120 N/cycle (then improved up to 30N), and allowed the accuracy of the impact force measurement to be assessed.

New sensors are being manufactured to be tested on a highway.

3.4 Data management and quality (WP 2.1, 2.2 and general input from all packages)

In most European countries WIM equipment is in use to collect traffic data for one or more purposes (Newton, 1999). An increasing demand on WIM data in Europe makes the exchangeability of these data between different countries and systems an important issue. Collection of WIM data is and will be done with a variety of devices and approaches. Thus, a very important issue is to transform the available data into a common European format. Due to the various measuring methods and site characteristics, there is a need for quality indices to qualify and classify the submitted WIM data. A whole Quality Assurance (QA-) system is required for that purpose. This part of the project provides the background and the procedures to enable the European WIM database and QA procedures to be implemented soon after the conclusion of the project. Some tools are not yet developed. The future implementation of these QA procedures and the maintenance and dissemination of the European database will highly depend on political decisions to be taken by the users and decision makers.

3.4.1 Inventory of data quality for existing systems

Investigation in and outside Europe showed that no automatic data Quality Assurance system was in use. In some countries, checking methods were developed and used (mainly in France and USA), or an automatic system is in preparation. The systems either in use or in preparation, are presented and discussed below.

In the United States, a huge quantity of WIM data was collected within the LTPP (Long Term Pavement Performance) project. In some cases, it was coupled with AVC (Automatic Vehicle Counting). The structure of the LTPP database (Hallenbeck, 1995b) comprises five levels, from 1, which contains annual aggregated data for pavement fatigue purposes without extensive information, to 5, which provide weekly highly desegregated data and hourly statistics. The designed QA-system (Hallenbeck, 1995a) uses a variety of summary traffic variables computed from the traffic data submitted by the State and provincial Highway

Agencies (SHA's). These variables are checked against known or expected target values. Submitted data that fall outside given ranges are considered as 'questionable' and are subject to further review. In fact they are flagged as questionable until a valid explanation for the abnormality is given by the SHA. If the traffic conditions are assumed to evolve at that site, the target values and/or ranges can be adjusted. In fact this system only detects malfunctioning equipment or loss of calibration.

The QA-system developed by the CETE de l'Est (France) for the French National SIREDO programme (Rambeau et al., 1998), allows the verification of the sensor performance. Indeed, WIM systems provide every day a file in which some parameters reflecting the proper functioning of the sensors are stored. This file is continuously checked by software. The parameters analysed are: the maximum registered scale factor of the sensors, the daily number of registered vehicles, the number of heavy vehicles, the date and hour, and the status of the station (functioning or not). The statistical information is checked. A program called 'MARTINE', automatically verifies the coherence of the content of different statistical data files based on comparison with the content of the same data files for other relevant periods.

3.4.2 Concept of the proposed QA-system

The aim of the QA-system for the European WIM database 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. The expected quality of the available data may be characterised by one or more "QA-parameters". The QA-parameters are indicators based on information about the weighing equipment, the pavement conditions and other parameters. The principles of the QA-system are as follows:

1. the supplier of the data fills out a sheet with the required information,
2. this information is entered in the QA software and automatically processed,
3. quality indicators related to the WIM data are provided.

The quality parameters calculation is performed under the auspices of the database manager. Implementation of new calculation methods due to a better understanding of influencing factors can easily and efficiently be done. Thus, users are informed about the (relative) quality of the data, without being overloaded with complex or excessively technical details.

According to the European Specification for WIM (COST323, 1999), the accuracy of a whole WIM system is defined in a statistical way, taking into account the sensors, the environment, the hardware and the software, and the climatic and traffic conditions. The accuracy is expressed with respect to the static vehicle weights and axle loads.

The main sources of differences between the WIM measurements and the static references are mainly due to:

(i) dynamics of the vehicles induced by the pavement roughness, and
(ii) environmental conditions (impact of climatic factors, road alignment and profile, pavement material behaviour, etc.).

In the QA-system, these pavement characteristics and environmental parameters are used as an input to estimate the level of confidence of the data. The QA-system has to take into account real or expected values and these values have to be updated with time. Missing information has to be dealt with and, for some values, an evolution of these values with time has to be defined. The relation between different measuring methods for the same parameter, for example evenness or deflection, is important. For each parameter, the most common measuring method in Europe will be chosen by default.

Vehicle dynamics induce a significant bias in the results (difference between the mean of the measurements and the true static weight, which can be removed by a proper calibration). Then, the scattering of the measurements also affects the accuracy. This scattering results from variations in the measurement conditions, even with the same vehicle, site, and sensor (repeatability or reproducibility conditions).

The accuracy is defined in a statistical way, as follows: a system is in an accuracy class δ if, with a specified probability (say α=0.95) the gross weight measurement falls in the confidence interval [Ws-δ; Ws+δ], Ws being the true static gross weight and δ the tolerance. There are different tolerances for the other criteria (single axle, group of axles, axles of group) in the same accuracy class. In fact α depends on the test conditions (COST323, 1999).

The accuracy can only be assessed (by testing) if WIM data and reference data (static weights) are available. If this information is not available, a subjective accuracy may be guessestimated.

The objective accuracy class is derived by mathematical formula from sample statistics (size, mean bias and standard deviation) of the individual relative error population. In the subjective approach, the bias is replaced by the calibration method (which provides a rough indication of the possible bias), and the standard deviation is replaced by a subjective classification of the measurement scattering such as: Bad (--),…., Excellent (++).

The input from site and the environment to the quality of WIM information is considered. The eventual effects of electronics and software on the performance is not considered. That is mainly dependent on the maintenance policy of the system, including financial or practical considerations.

Data available in the European database developed within the COST323 action (Siffert et al. 1998), provide information about the system and its environment. Information collected about the site and the WIM system can also be used in the QA-system.

However the QA-procedure requires additional information such as climate, road curvature, transverse slope, longitudinal slope and distance to last junction, type of pavement, deflection, longitudinal evenness, and transverse evenness.

3.4.3 Coherence tests in the database

The European database of WIM contains two main levels of information (Siffert et al. 1998). Level 1 includes 40 fields (site number, type of road, date, calibration method, etc.), all related to the WIM system and the site. The data of these fields are subjected to logical coherence tests such as checking that two different sites cannot have the same number, or that the last date of installation is greater than the first date of installation. Level 2 includes statistics on traffic flow, axle and vehicle loads computed generally over a year, but sometimes over shorter periods. Logical coherence tests or comparisons of statistics (mean, standard deviation, etc.) to reference values are performed.

3.4.4 Qualification of calibration procedures

In section 3.4.2 it is explained that an expected possible bias is considered in the subjective method to characterise the quality of the results, which depends on the calibration method in use. In order to classify the calibration procedures, the most important factors in the calibration process are provided by the data supplier by a questionnaire.

Five important items are defined to describe the calibration process:
- automatic self calibration on axle load,
- knowledge of the factors involved in the automatic calibration,
- knowledge of the traffic composition,
- frequency of the calibration,
- test plan used.

An automatic self calibration consists of computing continuously or periodically adjusting factors, based on a comparison between reference target values and measured values. However, a bias could still appear if, for example, the traffic composition or the average reference vehicle weights are changing, or if (temporarily) the population of reference vehicles is too small. Therefore a frequent verification of the automatic calibration system is necessary.

Then, the confidence in the calibration process, i.e., the level of confidence that the date is unbiased, is dependent on the combination of answers to the different items listed above.

3.4.5 Influencing factors

To quantify the effect of influencing factors, an experimental method was used. An experiment can be used to quantify the relationship between an output factor (accuracy) and several input factors (such as climate, pavement characteristics, vehicle type, etc.). For a given value of these input factors, enough measurements of dynamic weight allow the spread in the measurements to be calculated. Repeating this process for several other combinations of the input factors would then allow the relationship between accuracy and input factors to be calculated. However, it is not possible to vary factors such as climate, road geometry, or pavement characteristics (rather quickly). Another way that can be used to catch this kind of information is using a simulation model. The third way is to perform a subjective experiment, i.e., an experiment using a panel of experts that can rate the accuracy into a number, say of five, classes.

Assume that the potential accuracy of a WIM system based on a number of site factors can be classified as Excellent, Good or Acceptable. More classes can be added if necessary. A formula (Equation 25) provides for an arbitrarily combination of rutting and evenness, the probability that the outcome, and thus a WIM system, will be ‘excellent’, ‘good’, or ‘acceptable’. Using this probability, a measure of quality can be defined by:

$$\Pr\{Accuracy = i\} = \frac{1}{1+\exp(-\kappa_i + f(R,E))} - \frac{1}{1+\exp(-\kappa_{i-1} + f(R,E))} \quad (25)$$

where:

f(R,E)=0.62*Rutting + 0.31*Evenness

$\kappa_0 = -\infty$, $\kappa_1 = 3.14$, $\kappa_2 = 5.07$ and $\kappa_3 = +\infty$.

The experimental design and questionnaire are then defined. In order to keep the size of the questionnaire within acceptable limits, all sensors have been classified into three types: strip sensors, plates or scales, and bridges. For each type, the most important factors affecting the measurement accuracy have been selected and interaction between some parameters are defined.

For each sensor type, the factors assumed to have a major impact on measurement accuracy are displayed (WAVE 2001-3, Table 15): for example, IRI (International Roughness Index), speed variation, radius of curvature, etc.. For each factor, an interval (min, max), that has been chosen for its practical relevance, is shown. The factors together with three levels and interactions, determine the size of the experiment (i.e., the questionnaire). The answer to the accuracy of a measurement may be chosen within: bad, poor, acceptable, good, and excellent.

A panel of at least 20 experts per questionnaire is required to complete a questionnaire.

The experiment was carried out and the results analysed. However, the answers to the questionnaire were very difficult to obtain. Only 10 answers were received, and the questionnaire on bridge sensors was filled in only once. Despite this small amount of results, a statistical analysis was performed. This experiment gave a reasonably good indication about whether this approach can be used or not, and if the answers are more or less consistent with each other; moreover, a first rough indication about the relation between WIM measurement accuracy and the factors can be given.

As an example, the output and specific conclusions for strip sensors are given. The influence of the short term pavement temperature variation ΔT can not be proven, but the coefficient of influence of the radius of curvature was positive while all other coefficients were negative. This means that the radius of curvature affects the accuracy of the measurements.

3.4.6 Ageing factors

The quality of collected WIM data from a given site is not stable in time, due to evolution of some critical parameters. The layout of the site will generally not change during the lifetime of a WIM system. The road manager should take care that, if modifications are applied, it is reported to the WIM site operator. Modification in the site layout, such as lane width, physical and visual obstacles, but also speed limits, etc., could (should) change the behaviour of drivers and can affect the measurement results. For the WIM site manager, this information is relevant to attribute slight changes in measurement results to these modifications.

Some types of sensor are more sensitive to ageing than others. The sensitivity of capacitive mats and strips was found to decrease dramatically with time due to hardening of the isolators between the metal plates; many failures were reported on several sites. For piezoceramic cables a similar phenomenon was rarely reported, while piezoquartz strips are still too young to be fully known. A solution to face a low sensitivity loss consists of tuning the amplifiers or modifying calibration factors. These kinds of effect are hardly to be taken into account in a QA-system as described in this report.

The expected pavement deterioration can be taken into account. Using the parameters listed in section 3.4.4, such as type of pavement, location, climate and traffic conditions, a raw indication could be estimated, for example of the rutting after several years. Such a raw indication can only be used to decrease the expected quality of data when no actual information is available.

3.4.7 Conclusions

After inventory of existing WIM-data quality systems the conclusion was that, besides general checks on statistical data and coherence tests, no technology or procedures are operational for quality assurance of WIM-data. Also WIM-accuracy influence factors are generally not recorded.

With this background, the main influence factors were inventoried and discussed, in order to design a quality assurance system for a pan-European WIM-database, that is capable of labelling data files with a quality-mark, independent to the supplier. Recording influence factors by the local authorities maintaining the WIM-system(s) is the minimum support required to enable a centralised quality assurance system.

The performance of a WIM-system in terms of accuracy can be divided in two items, the bias an the standard deviation. For these items respectively the calibration method and the external influence factors the dominant subjects.

For the qualification of influence factors can be concluded that relation between evenness an dynamic impact force is a relative well known phenomena with a direct impact on the measurement accuracy (i.e. the standard deviation). For other factors (i.e. climate) only some general ideas are available. These factors should be recorded as recommended before. Due to the complex relations between the different factors and types of WIM-systems designing a scientific based QA-system is not possible within the state of the art of WIM in Europe.

An alternative method was introduced, using experts opinions by means of an experimental method. It can be concluded that such a system, even with relatively little response of experts, is useful. The design of the used questionnaire is critical.

The calibration procedure is the main factor concerning the (possible) bias in a WIM-system. The qualification procedure for calibration procedures is prepared, also taking into account the results of WAVE (2001-5): *Calibration of WIM-systems*.

The proposed procedures for qualifying WIM-accuracy can be used as a basis for the European WIM-database. Recording of the main influence factors is required to improve the system and therewith its performance.

4. IMPLEMENTATION, DISSEMINATION AND BENEFITS FOR THE USERS

4.1 Dissemination of knowledge, data and experience

The WAVE project consortium had considerable overlap with the membership of the COST 323 action and this provided a significant vehicle for the dissemination of the results. The report on WIM Needs and Requirements prepared by the COST323 group established what was of greatest interest to European road management authorities and ensured the relevance of the WAVE research.

The COST 323 action also facilitated the dissemination of the WAVE results through the organisation of the Second European Conference on WIM. This provided a major international forum for the presentation of the project results. Pre- and post-proceedings were published by the European Commission in English and French (COST323, 1998a, b, c) and widely distributed within Europe and internationally.

In addition to this conference, the WAVE consortium organised two European seminars to keep national authorities and the WIM industry informed of results from the WAVE research. The mid-term seminar in Delft (WAVE, 1997) provided a first introduction to the detailed work in progress at that time and a useful mechanism for dissemination and interaction between the consortium and the industry at large. On completion of the WAVE project, a larger final symposium was organised in Paris, with more than one hundred participants and a published book (Jacob, 1999b). 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 Washington DC, January 1998, NATMEC'1998 (North American Traffic Monitoring Exhibition and Conference, Charlotte, North Carolina, May 1998), the 5th International Symposium on Heavy Vehicle Weights and Dimensions (Brisbane, Australia, April 1998), the 2nd ERRC (European Road Research Conference, Brussels, June 1999), and in Vehicle/Infrastructure Interaction conference in Zakopane (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. Additional results will be presented in the 3rd ICWIM (International Conference on WIM, Orlando, Florida, May 2002).

Within the project itself, most of the existing and developing WIM technologies were implemented as prototypes or in full scale tests, throughout several countries. WIM manufacturers and users were involved, and after the project completion, some of these tests were continued: the CET (and CMT part of the COST323 action) were extended for another one and one half year period (1999-2000), and the WIM systems were up-dated or improved according to the conclusions of the first period. Most of the manufacturers gained experience from these tests while the customers and users became more confident in the marketed products. As an example, new markets were opened in several countries (inside and outside Europe) for the piezo-quartz WIM sensor, after it was successfully tested in Sweden for a full year.

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. Statistical data on vehicle and axle loads are or will be available for various applications. 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 to loose the benefit of the work completed by WP2 of WAVE.

4.2 New technologies implementation and dissemination

The concept of Multiple Sensor WIM (MS-WIM), introduced in the UK in the late 80's, was enhanced in the project, by the introduction of two new algorithms. They both intend to better take into account the vehicle/pavement interaction and to give a more accurate estimate of the static weights. These 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. MS-WIM is a unique approach. 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.

Behind WAVE, three countries started large projects (from 0.5 to 2 M Euros) to further develop and implement MS-WIM systems combined with video for enforcement: The Netherlands, with a project supported by the ministry of Transport and conducted by the DWW, France, with a project supported by the ministry of Transport (Ground Transportation Division) and conducted by the LCPC, and Germany with a European project on trials of MS-WIM systems in Bavaria.

The technology of Bridge WIM (B-WIM) was in its infancy at the onset of WAVE. Little development had taken place in the United States since the initial concept was published there in 1979. Some other sporadic developments had taken place in Australia and Europe (Ireland and Slovenia). The WAVE project transformed B-WIM from this early stage of development into a mainstream WIM technology at a level comparable with all others.

A major focus of the WAVE B-WIM research was on the improvement of accuracy of B-WIM systems. A number of major sources of inaccuracy were identified and addressed. Considerable research effort was expended on the dynamics of the truck-crossing process. This involves truck bouncing and rocking, bridge vibration and the interaction between the two. Computer models were developed and validated to simulate the process and B-WIM algorithms developed which take account of dynamics in their calculation of static axle weights. Other sources of inaccuracy were also addressed such as transverse location of trucks in the wheel track. Two dimensional models of orthotropic bridges were developed to allow for strain variations due to this and optimisation methods applied to remove or reduce the effect. Full scale field tests were used to measure the accuracy of typical B-WIM systems and they were found to be at consistently high levels.

The range of bridge types that are suitable for B-WIM was extended considerably. A specific algorithm was developed for orthotropic bridges while conventional algorithms were used in validations of the method on a wide variety of other bridge types: integral or frame bridges, box culverts, skewed bridges, concrete slabs, concrete beam and slab and medium span composite box girder bridges. The durability of B-WIM systems was substantially improved with the development of Free of Axle Detector (FAD) B-WIM systems - WIM systems which involved nothing on the road surface. This concept of having all instrumentation attached to the underside of the bridge deck has obvious durability and safety advantages. Initial field trials demonstrated the feasibility of the concept and theoretical studies showed the range of spans and bridge types which show greatest promise for this approach. A full-scale FAD system was developed for orthotropic bridges.

The SiWIM© system for Bridge WIM is likely to be fully commercialised and its open architecture will be of great benefit for other developers of B-WIM algorithms. The principle of commercial B-WIM is gaining widespread acceptance. It can be applied on most types of the bridges, including orthotropic-deck bridges, and has many advantages in cold climate regions.

The fibre optic (FO-)WIM system was greatly developed in the WAVE project, even if some delay occurred because of a major change of partner within the Alcatel group. The design of the FO-WIM sensor was definitively formalised and successfully tested, both in the laboratory under calibrated forces and in a parking area under true vehicle wheels. The whole opto-electronic unit and software, delivering the light and doing the signal processing and analysis by interferometry (counting of fringes) was also 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.

The findings of WP4 on FO-WIM are of major interest, as many organisations around the world are trying to develop FO-WIM systems for the past decade. Almost all the current research works are focused on a rather simple technology (light attenuation), which is not accurate enough for WIM of class C(15) or better, according to the European Specification. The marketed systems are currently specified only for vehicle classification. The technology developed by Alcatel before WAVE, 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 high quality existing 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.

Depending on the market size and conditions, the manufacturing of the FO-WIM system may be concentrated or disseminated in several countries, as the company Alcatel is worldwide. In any case, the dissemination of such a new technology may induce a large amount of business, and generate jobs within and outside Europe.

5. LIST OF DELIVERABLES

No.	WP 1.1. DELIVERABLES	Access
1	State of the art on the sensor performance and previous experience on MS-WIM - *in progress reports of WAVE, proceedings of the ICWIM2 (Lisbon, 1998) conference, of the Delft mid-term seminar (1997) and Final Symposium of WAVE proceedings (Paris, 1999).*	Public
2	Theory for MS-WIM design and description of two new algorithms (signal reconstruction - SR - and maximum of likelihood - ML -) - *in the WP1.1 final report + various published papers (see N°1 and journal papers)*	Public
3	Instrumented sites with MS arrays : Metz (F, A31) with 16 piezo-ceramic sensors (1997-99), Abington (UK, A34) with 20 capacitive sensors; another site (F, RN10) instrumented during the OECD DIVINE project was also used in WAVE.	On request, with the permission of the owner
4	Collection of data on axle loads and vehicle weights on each MS-WIM array, with pre- or post-weighed in static lorries (a few hundred lorries on each site)	On request
5	Progress reports on the experiments on the MS sites	Public
6	Prototypes of operational MS-WIM systems - one prototype delivered by ECM (A31, FR) and one by Golden River (A34, UK); however, the new MS-WIM algorithms are not yet implemented in the prototypes but are implemented on PC's as post-proceeding.	MS-WIM systems on sale by manufacturer
7	Performance specifications for MS-WIM systems : class A(5) according to the European Specification on WIM (COST323) for enforcement and legal application; class B+(7) was achieved in WAVE and may be accepted as a first step.	Public
8	Final report on MS-WIM (LCPC, CUED) - *WP1.1 report*	Public
9	Requirements and legal issues for enforcement using MS-WIM systems - *some input was given by WAVE, and the work continues in France, Germany and The Netherlands in the frame of national or European projects.*	Public

No.	WP 1.2. DELIVERABLES	Access
1	Instrumented Autreville (FR) bridge and measurements (LCPC)	Public
2	Instrumented Belleville (FR) bridge and measurements (TUM,)	Public
3	Four instrumented bridges in Slovenia and measurements (ZAG)	Public
4	Instrumented Fischerdorf bridge (D) and measurements (TUM)	Public
5	Instrumented Alean bridge near Luleå (S) and measurements (TCD/UCD) – *in M.Eng.Sc. thesis (McNulty 1999), journal paper submitted to Institution of Civil Engineers (UK).*	Public
6	Reports on extension of B-WIM to Orthotropic deck and Other Bridges - *in progress reports of WAVE, proceedings of the ICWIM2 (Lisbon, 1998) conference, of the Final Symposium of WAVE proceedings (Paris, 1999), and in the final report of the WP1.2.*	Public
7	SiWIM-E© software, a frame which allows to implement B-WIM with various algorithms on any type of bridge. It manages the data acquisition, signal processing, displays the results and stores them into files(ZAG)	On sale by ZAG
8	Algorithm to improve the accuracy of B-WIM systems taking into account the bridge dynamics (TCD)	Public??
9	Algorithm for a B-WIM system on an orthotropic deck, using a complete optimisation method (LCPC)	Public
10	Method of B-WIM calibration (ZAG, TUM) - *presented in the WP1.2 final report*	Public
11	Final report of the WP1.2 (TCD, ZAG, TUM, LCPC)	Public

No.	WP 2. DELIVERABLES	Access
1	Reports on data quality assurance (WP2.1) - *in progress reports of WAVE, proceedings of the ICWIM2 (Lisbon, 1998) conference, of the mid-term and Final Symposium of WAVE proceedings (Paris, 1999), and in the final report of the WP2.*	Public
2	Report on database (WP2.2) - *in the Final Symposium of WAVE proceedings (Paris, 1999), and in the final report of the WP2.*	Public
3	Quantifying WIM Measurement Accuracy - report in co-operation with third party: CQM (project report no: E1650-2) (1)	Public

(1) This deliverable was not supported in the 'WAVE's budget, and thus was not a full part of the contract. It was sub-contracted to a company, on the basis of a free-cost work, with a counterpart for this company as an advertisement and a background knowledge for further development in this field. This part was done instead of the planned work for demo version of the software.

No.	**WP 3.1. DELIVERABLES**	**Access**
1	Test site of Alean, near Luleå, with four WIM systems installed and calibrated, June 97-June 99 (SNRA)	On request, with the permission of the owner
2	Test sites in St Gothard and San Bernardino in the Swiss Alps, with one WIM system installed and calibrated on each site (ETH)	ditto
3	Data of the 1st Summer, the Winter and the 2nd Summer tests (CET, Alean 97-98) (SNRA)	Public
4	Data of the tests in Switzerland (1996-98) (ETH)	Public
5	Reports on the CET in Alean and on the Swiss tests, and analysed data - *in progress reports of WAVE, proceedings of the ICWIM2 (Lisbon, 1998) conference, of the Final Symposium of WAVE proceedings (Paris, 1999), in the final report of the WP3.1, and in published papers.*	Public
6	Final report of the WP3.1 (SNRA, VTT, ETH, BRRC)	Public

No.	**WP 3.2. DELIVERABLES**	**Access**
1	State of the art report: existing calibration methods (VTT)	Public
2	Calibration data of the MS-WIM (A31 in FR) site with the instrumented vehicle of the VTT (LCPC, VTT)	Public
3	Report on the calibration of the WIM systems in Alean (CET) (SNRA, VTT)	Public
4	Proposal and evaluation of a new calibration method by axle rank (LCPC) - *in the Final Symposium of WAVE proceedings (Paris, 1999), and in the final report of the WP3.2.*	Public
5	Final report of the WP3.2: Recommendations for calibration of WIM systems (VTT, LCPC)	Public

No.	WP 4. DELIVERABLES	Access
1	FO-Sensor sample and prototype (Alcatel)	Presented in public
2	Characterisation of the FO-sensor, installation, calibration and testing procedures (LCPC, Alcatel) - *in progress reports of WAVE, proceedings of the ICWIM2 (Lisbon, 1998) conference, of the Final Symposium of WAVE proceedings (Paris, 1999), and in the final report of WP4.*	Public
3	Mathematical model (simulation modelling of the sensor in its environment) (LCPC, Alcatel) - *in progress reports and in the final report of the WP4.*	Public
4	Optoelectronic head prototype (Alcatel)	Presented in public
5	Multiple Sensor head design (Alcatel)	On request, with the permission of the owner
6	Installed sensors and optoelectronic head assembled as a prototype system in a parking area in Saintes (FR) (Alcatel)	On request, with the permission of the owner
7	Test results of Saintes with a few vehicles (LCPC, Alcatel)	Public
8	Mathematical model of data processing	Public
9	Final Report of the WP4 (LCPC, Alcatel)	Public

General Deliverables

- Web site (ZAG) http://wim.zag.si/ (section WAVE)
  (+ a few pages on http://www.lcpc.fr/LCPC/Collaboration/wave/)
- CD-ROM of the project (BRRC)

6. CONCLUSIONS, RECOMMENDATIONS AND FUTURE NEEDS

6.1 Conclusions

The WAVE project on Weigh-in-motion of Axles and Vehicles for Europe, has been rich in theoretical and applied works, experimentation and data collection and analysis. All have shown considerable advances in recent years, and also the progress still to be made. Weighing road vehicles was initially a priority for infrastructure design and maintenance, but became recently a higher priority for ensuring fair competition between various transport modes and companies and to enforce the harmonised load legislation throughout Europe.

Road safety is also a high priority and requires an efficient means to control lorries. An overloaded vehicle does not handle as well as a normally loaded vehicle, and weight is an aggravating factor in an accident.

WIM may also help to ensure fair competition in transport, by providing automated controls which has become necessary to face the huge increase in heavy goods vehicle traffic.

The preservation of infrastructure is also a high priority and a difficult task, under budget constraints. Even though there has been much progress in the design and construction of infrastructure, which is being made stronger and stronger, it cannot bear unlimited weight under any conditions. Larger loads exponentially speed up the ageing and wear of pavements and the fatigue of steel and composite bridges, leading to large rehabilitation costs to the community.

Until now, static weighing has been the only way to detect overloads. This naturally has its limits and, in spite of the efforts made, the number of weighings is still far too small for enforcement to have the dissuasive effect expected of it. Furthermore, static checking requires intercepting and stopping vehicles and guiding them to checking areas and, on some main roads and motorways, this is almost impossible and can be dangerous. Moreover, these operations are becoming more and more cumbersome and more and more expensive, revealing the limitations of the static checking system. It is therefore essential to find new solutions so that the number of vehicles checked can be substantially increased.

WIM seems to be an ideal means of addressing these problems, but 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. Bridge (B-)WIM may also be an alternative solution for that objective in some locations, as bridges are generally key points in the road network and difficult to escape. Further, B-WIM systems, particularly FAD (Free of Axle Detector) B-WIM systems, can be undetectable to the road user.

WIM systems can function with various types of sensor fixed in the pavement. They are, however, sensitive to the dynamic effects induced by the road profile. To increase the precision of the static weight estimates, use is made of the multiple-sensor weighing concept, in which the information from several successive sensors is combined. Research was conducted in France, by the LCPC, and in the United Kingdom, by the CUED. Two new algorithms were developed and tested using results gathered at a few European test sites, in France and the UK. 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.

One of the limitations of the precision is due to the sensors themselves, but new technologies were either developed or tested in WAVE and open promising solutions. Among them, the piezo-quarz sensors, developed in Switzerland before WAVE, were successfully tested in Sweden under harsh climatic conditions (CET), and were shown to give very stable results throughout a year, despite large temperature variations.

The fibre optic sensors also provided encouraging preliminary results, with a design well adapted to accurate weighing. The feasibility of a whole FO-WIM system was proven in a parking area on a real pavement and with commercial vehicles. The marketing of this technology is expected in a 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. For the monitoring of overloads or collecting the traffic data, this system could be relatively inexpensive and could be implemented widely, 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. Today, more and more types of bridge can be used to weigh trucks with good precision, and further improvements are under study. Currently, the precision attained is easily comparable to that of weigh-in-motion systems with sensors in the pavement. These systems can be installed without interrupting traffic or with only minimal interruptions of traffic. They provide results of the same quality regardless if they are installed permanently or they are moved from site to site and the Free of Axle Detection (FAD) type is not detectable; they are 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 requested funds for bridge repairs or replacements and to reduce the corresponding traffic disturbances.

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 period of the 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 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 permanent load transfers occur while the vehicles are travelling at speed, which may disturb the calibration of WIM systems. Therefore, a calibration "by axle rank", suggested in the European Specifications on WIM but never tested, 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.

The investigations carried out on existing Quality Assurance systems of WIM data in the US and in France, led to the design of an original QA system. 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 sessions or checks. 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.

6.2 Recommendations and future needs

Some recommendations should be made on the use and application of WIM data:

(i) to provide statistical or detailed information on traffic flow and vehicles, to help road management and traffic monitoring;

(ii) to improve pavement design models, especially models used to predict the wearing of pavements, with a view to optimising the scheduling of their maintenance;

(iii) by the managers of bridges, to determine the loadings to which their structures are subjected and hence to determine the safety of the structure for the site-specific traffic;

(iv) to accurately screen, and later directly enforce, overloaded vehicles.

For each application a specific accuracy may be required, typically class D(25) or D+(20) for (i), C(15) or B(10) for (ii) and (iii), and B+(7) or A(5) for (iv).

The implementation of the proposed Quality Assurance system in the European database of WIM should ensure the access to a large amount of reliable data for the users and decision makers. European countries and road authorities (i.e. WERD) are concerned with keeping such a database available for future use, containing both the experimental results gathered in WAVE and COST323, and much more data collected by all European WIM users. It would be regrettable if a collective solution could not be found to a question that is of collective interest.

The stages of standardisation and certification must be addressed, and it is one of the tasks of the applied research organisations to contribute to this with their expertise. Behind the procedure engaged at the end of the COST323 action with the CEN (Preliminary Questionnaire on the European Specifications on WIM, to make a European Standard), an action was initiated with American, Australian and Asian experts, and should be supported by some International Organisation, to make an International Recommendation on high-speed WIM, based on the ASTM 1318 US Standard and on the COST323 Specifications. The OIML (International Organisation for Legal Metrology) already proposed a draft recommendation for low-speed WIM applied to trade.

The most demanding application of WIM, not yet fully covered by existing marketed systems, is the overload enforcement (iv). The findings of WAVE provided some promising means of combining enhanced algorithms for multiple-sensor (MS-)WIM, and new WIM sensors (fibre optic: FO-WIM) or approaches (bridge: B-WIM). The project solved a large number of questions and issues, but also identified some others. Additional applied research work seems necessary to get a fully operational WIM system of class A(5), which may be submitted to a legal type approval for direct enforcement.

Several related issues remain, however, to be explored: automatic vehicle identification, interception of overloaded vehicles for charging and possibly immobilisation. Some countries have already begun work on this. For example, in the Netherlands, the VIDEO-WIM pilot project can identify overloaded trucks by weighing them at high speed and can draw up a list of offenders. The transport firms are then informed of the offences committed and warned that they are liable to an inspection of their premises. An experiment on this approach has also started in Eastern France.

For the future, on-board weighing would allow measurement of the static weight, either during the many times a vehicle is stopped, or while moving, and indicate, in addition to the weights, the impact forces actually applied to the pavements. In the longer term, and in the context of smart vehicles and roads (ITS), it may be envisaged that when the impact force of an axle exceeds some specified threshold (e.g. the maximum authorised static weight plus 5, 10, or 15%), the driver is warned to reduce speed temporarily.

In addition to the interception of overloaded vehicles, WIM systems may have applications in the field of road tolls, a subject mentioned regularly at European level. Knowing vehicle weight and length, axle loads and spacings, would allow a new toll mode to be designed, more realistic in terms of space occupancy and wear of infrastructure. If this is done with tolls, the use of transponders with smart cards could also be considered for automatic electronic toll collection. But complementary studies will of course be necessary. These transponders, on board trucks, could read the vehicle's electronic registration card and thus ascertain the maximum authorised weight during a passage through a high-speed WIM system. If there were an offence, the transponders could doubtless transmit a lot of other information of interest such as driving times, the date of the last technical inspection of the vehicle, etc.. Naturally, it will be necessary to obtain the proper authorisations from the *ad hoc* commissions to protect privacy from encroachment by information technologies.

A new challenge concerns the weighing in motion of aircraft, in particular for the design and management of airport pavements and installations. A technology transfer is being operated from road transport to air transport. Some interest was already been expressed in France and in The Netherlands, and this topic could be the subject of a future European collaboration.

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FIGURES

TABLES