European **C**ommission

DG VII - Transport

4th Framework Programme
Transport

Weigh-in-motion of **A**xles
and
Vehicles for
Europe

RTD project, RO-96-SC, 403

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

Report of Work Package 4

Optical WIM systems, technology for the future

Laboratoire Central des Ponts et Chaussées October 2000

THE PROJECT

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

1. Origin of the project

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

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

2. Objectives

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

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

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

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

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

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

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

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

3. Project organisation and means

The consortium involved 6 Contractors and 5 Associate Contractors:

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

Contractors

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

Associated Contractors

Belgian Road Research Centre - BRRC - Belgium
Technische Universitaet Muenchen - TUM - Germany
Technical Research Centre of Finland - VTT - Finland
Swiss Federal Institute of Technology - ETH - Switzerland
National Building and Civil Engineering Institute - ZAG - Slovenia

All together, more than 15 senior scientists and engineers, 25 Ph.D. students, post-doctoral or young engineers or researchers, and many technicians were involved in WAVE. Some subcontractors were SME (Small or Medium Enterprises), manufacturers and/or vendors of WIM systems or services; they were therefore self-motivated and interested in the output and deliverables of the project.

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

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

The detailed organisation of the WPs is described below:

WP1. Accurate estimation of static weights using WIM systems

- WP1.1. Multiple Sensor WIM (MS-WIM) - *leader: CUED / co-leader: LROP/LCPC*
    a. New and improved theories
    b. Validation using experimental data

c. Tests of MS-WIM systems
d. Specifications and legal issues

WP 1.2. Bridge WIM systems (B-WIM) - *leader: TCD*
a. Increased Accuracy for Typical Bridges
b. Extension of B-WIM to Orthotropic Decks
c. Extension of B-WIM to Other Bridges
d. Dynamic Analysis for Typical Bridges
e. Calibration

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

WP2.1. WIM data quality assurance
a. Analysis of existing quality systems
b. Site quality
c. System quality
d. Calibration procedures
e. Data quality

WP2.2. WIM data format and database structures
a. Submitted data format
b. Harmonisation procedure
c. Description of two database levels
d. Database management and maintenance

WP3. Consistency of Accuracy and Durability

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

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

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

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

WP4.2. Optoelectronic Head
a. Design

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

WP4.3. Data Acquisition and Processing Unit

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

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

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

4. Project output

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

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

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

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

Report on the WP 4

This report was drafted by JM. CAUSSIGNAC and is edited by LCPC.
The main contributors are: J-M. CAUSSIGNAC (LCPC), J-C. ROUGIER (ALCATEL), and S. LARCHER (AML) as sub-contractor……

Outline

1. INTRODUCTION

The fourth package, mainly supported by a private industrial company (Alcatel Group), with company AML, as sub-contractor, and a partnership with LCPC, is itself a full R&D project.It will lead to the development and manufacture of a relevant European WIM system., based on using single mode optical fibre as sensitive element for sensing. A new sensor design was made after testing a lot of prototypes. Numerous laboratory tests were performed to assess its performance. The opto-electronic head was also developed during the project, as well as the required software, and the developed device was designed, according to needs, to allow to be inserted into a MS-WIM optical fibre station. In fact, the design of MS-WIM is made of using the multiplexing ability of fibres. For this, technologies were transferred from techniques applied to communication optical links.

The Research Centre of the Alcatel Group worked since 1985, on fibre glass properties in order to apply them to high data flow for long distance transmissions. The optical fibre behaviour caused by mechanical stresses and strains systematically was studied. The idea to use a few optical fibre properties to measure physical parameters was born at the period. A weigh-in-motion sensor based on using optical fibres had been developing for the beginning of Wave project in a partnership between the Laboratoire Central des Ponts et Chaussées, depending on the French Ministry of Transport, the Alcatel Group and the AML Society as sub-contractor of Alcatel. The sensor uses light birefringence in optical fibre which undergoes a mechanical strain. The paper describes theoritical principles, sensors, optoelectronic head, data processing, software and shows main obtained results at laboratory and on site. A summary of test results is given, showing important advantages, which enables us to expect new possibilities, and new implementations : estimation of tyre pressure, reliable classification of vehicles, calculation of static weight with a multi-sensors grid.

A first generation of prototype sensor was installed on the RN 10 close to Paris, some 30 months ago, and extensively used to base further developments. Beside experimental confirmation of capabilities of the sensor to achieve sophisticated vehicle load profile determination, refined analysis of measurements was made to improve the design. A second generation of sensor had been thus developed, to correct some of waveform problems observed under high loading conditions. Tests produced satisfactory results, and sets of new sensors installed on experimental test site (parking close to Alcatel Company at Saintes (France)). In parallel, work was completed in sensor processing, in view of achieving the design of an operational WIM station.

2. PRINCIPLE OF MEASUREMENT

2.1 Sensor principle

Some transparent materials like fused silica have the property to become birefringent under external actions. Then, two waves can propagate independantly with distinct polarizations ; if we select one polarization direction at the fibre end by the aid of a linear polarizer, the transmitting light intensity varies as the birefringence moves, resulting in a fading phenomenon. This is referred as polarimetric fringes in optical systems because of the successive minima and maxima in light intensity.

If noting n and λ for respectively the refractive index and the operating wavelength of the optical fibre of length l, 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:

$$\Delta n = \frac{(1+\gamma)(P_{12} - P_{11})}{2E} n^3 . [\sigma_X - \sigma_Y] \qquad (1)$$

where the following parameters describes the mechanical characteristics of the optical fibre :

- E is the Young modulus,
- γ is the Poisson ratio,
- P_{12} and P_{11} are the photoelastic constants.

When a linearly polarized light comes into the fibre, the birefringence results in a fluctuating intensity (fading) which is caused by the phase shift between the two characteristic polarizations. The phase shift by unit length is given by equation 2.

$$\frac{\Phi}{l} = \frac{2\pi}{\lambda} . \Delta n \qquad (2)$$

The sensor uses the photo-elastic effect in glass : a vertical compressive force applied to glass changes light velocity in optical guide, because of refractive index moving (Figure 1).

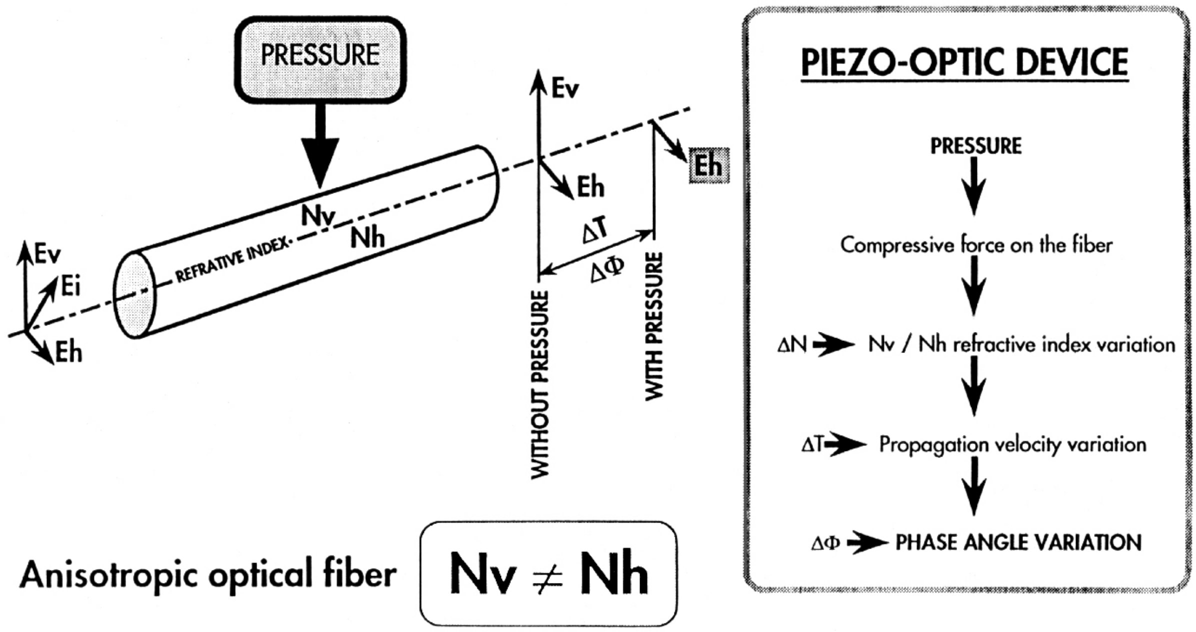


Figure 1 : Piezo-optic sensor design

This induces the separation of two propagating modes : the faster mode (vertical) and the lower one (horizontal). The incident light, Ei, is linearly polarized in a plane at 45° angle to the horizontal plane. At the fibre end, after light propagating along length L, a delay is caused between the two modes and creates a phase shift Φ between the two transmitted waves, as expressed :

$$\Phi/L = 2\pi.\Delta n/\lambda$$
$$E_v = E_0.\exp(j\omega t) \; ; \; E_h = E_0.\exp(j\omega t + \Phi)$$

An optical receiver connected at sensor end will see sum of two modes, a photo-diode transducer converts light power into an electric current I_t so :

$$I_t = k\,(E_v + E_h)(E_v + E_h)^* = E_0^2\,(1 + \cos(2\Phi))$$

After travelling through the sensitive optical fibre, light is coming back towards receiver by a non sensitive fibre placed inside the same bar. As like that, sensor needs only one connecting cable to operate (Figure 2).

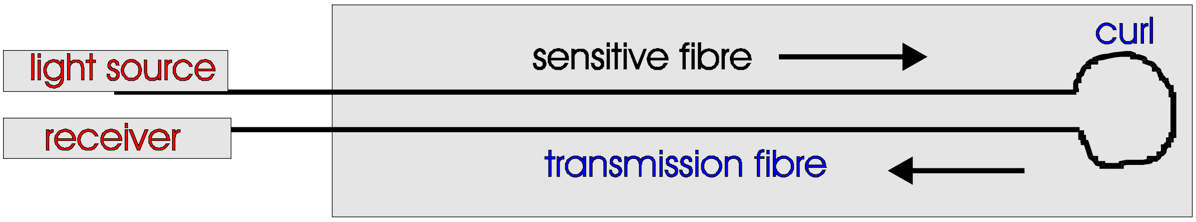


Figure 2 : Transmission mode used for connecting optical fibre to optoelectronic head

In order to measure a strength, a single mode optical fibre is placed between two metal ribbons tight together along the two edges. The effect of bending the ribbons provides a compressive force on the fibre (see & 3.1).

With these conditions, the horizontal axis of the fibre does not receive a force, while the vertical axis gets the force to measure. Which causes a constant light velocity for the horizontal axis and a variable light speed on the vertical axis.

A coherent, linearly polarized light beam is inserted into the fibre with a 45° angle by respect of vertical axis. The light beam travels along the fibre with two different speeds, as shown above, so, at the end of the fibre, we observe a delay between the two modes, or a rotation of the received light polarization. To detect phase variations, an analyzer is placed in front of the receiver in order to select one polarizing 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 3).

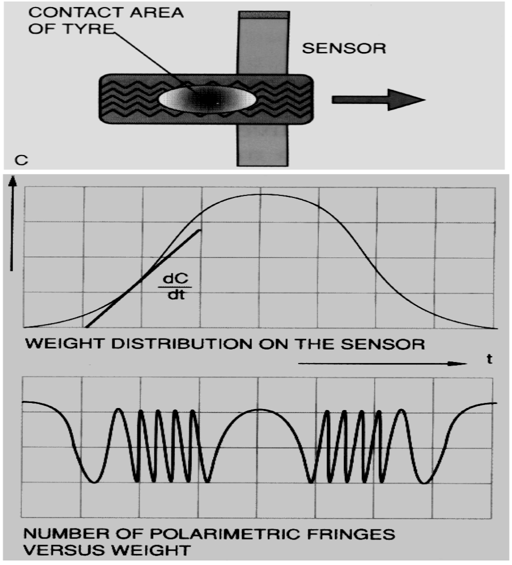


Figure 3 : Example of typical signal from optical fibre sensor

Simple fringe counting is used to determine the change in birefringence, relating in particular to the weight of one wheel. A typical vehicle signature is characterized by a number of fringes M, which depend on the weight, crossing tiem T (versus speed), and tyre inflation (Figure 4).

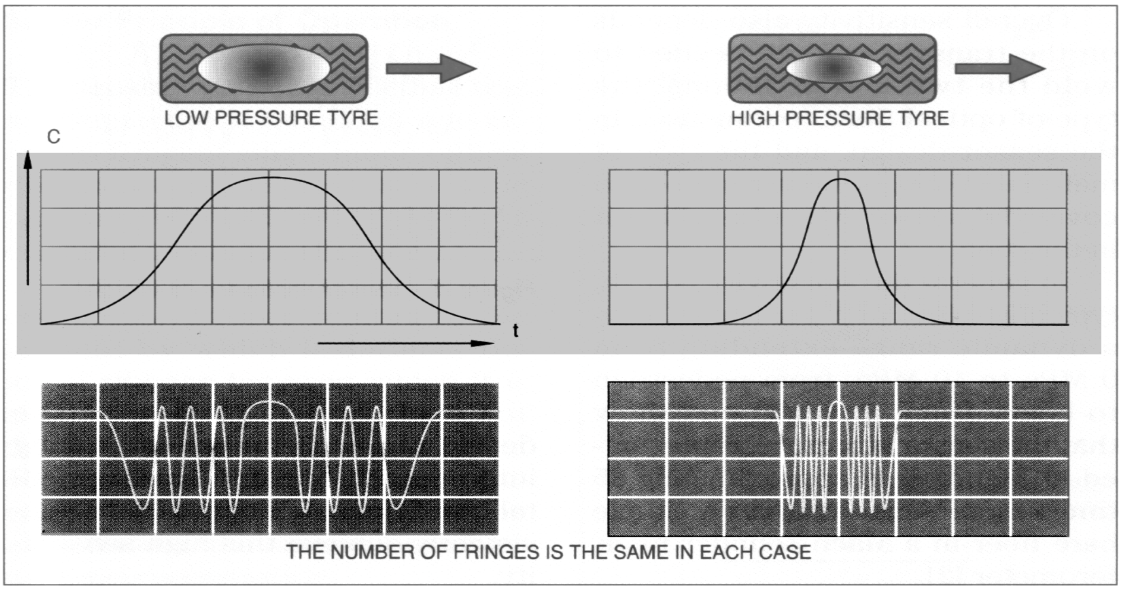


Figure 4 : Pressure tyre influence for an identical weight

When a vehicle passes over the sensor the signature is interpreted as follows :

- first fringe shift corresponds to increasing load as tyre rolls on to sensor,
- continuous signal indicates quasi-static pressure while tyre is centred on sensor
- second fringe shift corresponds to decreasing load as tyre rolls off of sensor.

The total vehicle dynamic load is calculated as the sum of individual wheel weights.

2.2 Signal processing

Operational acquisition requires and optimum choice of triggering conditions, sampling frequency f_S, record duration, and data processing architecture. Those parameters are to be selected on the basis of vehicle parameters (essentially range of speed and axle weight). This in turn determine the acquisition strategy and processing hardware to be used. The instantaneous phaseshift $\Delta F(t)$ as measured by the sensor is proportional to the instantaneous load $P_{(t)}$:

$$[\Delta\Phi_{(t)}]/2\pi = KP_{(t)} \qquad (1)$$

where constant K, expressed in cycle/kg is typically 0, 1 and 0, 16 for available sensors, or equivalent between 6 and 12 kg/cycle. The constant value for each sensor is determined by calibration. The observed signal is expressed :

$$y_{(t)} = A + B\cos(\Delta\Phi_{(t)}) \qquad (2)$$

what corresponds to a fringe frequency :

$$f_{\phi(t)} = [1/2\pi\,][d\Delta\Phi/dt] = K\,[dP/dt] \qquad (3)$$

Coefficients A and B in (2) are also supposed to be known, and are kept updated in an adaptative way during processing. They are deduced from extremum values (A + B) and (A - B) of signal.
Acquisition conditions - and in particular sampling frequency fs - depend upon maximum fringe frequency, and thus is related to load variation stiffness.

2.3 Acquisition hardware

Such rates prohibit acquisition and processing for load reconstruction in real-time to be directly made on a PC like computer. For real-time processing, a dedicated electronic hardware has been designed, and is currently being developed. The principles are briefly described as follows :

- a single-mode evanescent field coupler is used to produce a $\pi/2$ phase delay on one polarization direction. After recombining and detecting, this is used to generate another observed signal :

$$z_{(t)} = A - B\cos(\Delta\Phi_{(t)}) \qquad (4)$$

From there, simultaneous consideration of cosine and sign of sine allows removal of phase ambiguity and phase extraction as :

$$\Delta\Phi_{(t)} = \varepsilon_{(t)}\,\mathrm{Arc}\cos(y'_{(t)}) + k_{(t)}\,2\pi \qquad (5)$$

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.

3. EQUIPMENT DESCRIPTION

3.1 Equipment design

Before making equipment, sensor design deduced in simulating sensor behaviour under loading by theory. These models validated by experiment both at laboratory and on site. Studies were carried out :

- by LCPC and CCT Trappes

to develop a model of sensor by means finite element method in order to optimize the design and to simulate its metrological behaviour under various environmental conditions. This allowed to determine main mechanical characteristics of materials to be used, components geometry, to estimate stresses and strains within sensitive element of optical fibre, …. Two cases was defined, alone and attached sensor to the road. We were able to provide informations to improve both sensor design and installation process on site.

- by Alcatel Group

to choice and test optical and optoelectronic components and to improve the system with particularly the design of a devoted electronic card to perform numerical treatment in real time, and at last to simplify and make device,

- by AML, sub-contractor of Alcatel Group

to acquire and to treat data.

Sensing ribbon is made of a single mode optical fibre squeezed between two metal strip welded together by a crimping technique. Optical guide is preloaded with a compressive force due to metal strip elasticity. The design allows to collect received forces and to apply sum of them in two points of a fibre diameter, in a constant vertical plane all along sensor (Figure 5). Sensitive ribbon is placed within a composite U profile, filled with an elastomer material. The bar is 3,71m long, an optical cable is connected at one end. On site sensor is attached to be flush with road surface (Figure 6). A groove is cut in asphalt. Sensor is laid down and a bounding made of epoxy resin and sand is put around sensible bar (Figure 7).

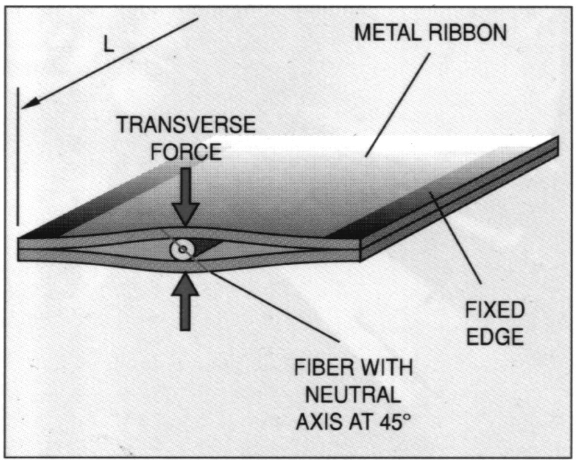


Figure 5 : Sensitive element of the sensor

The sensor design was deduced from modelling by finite element method. We defined geometry of components and material characteristics to be used and their behaviour upon various conditions in order to choice the best compromise between them.

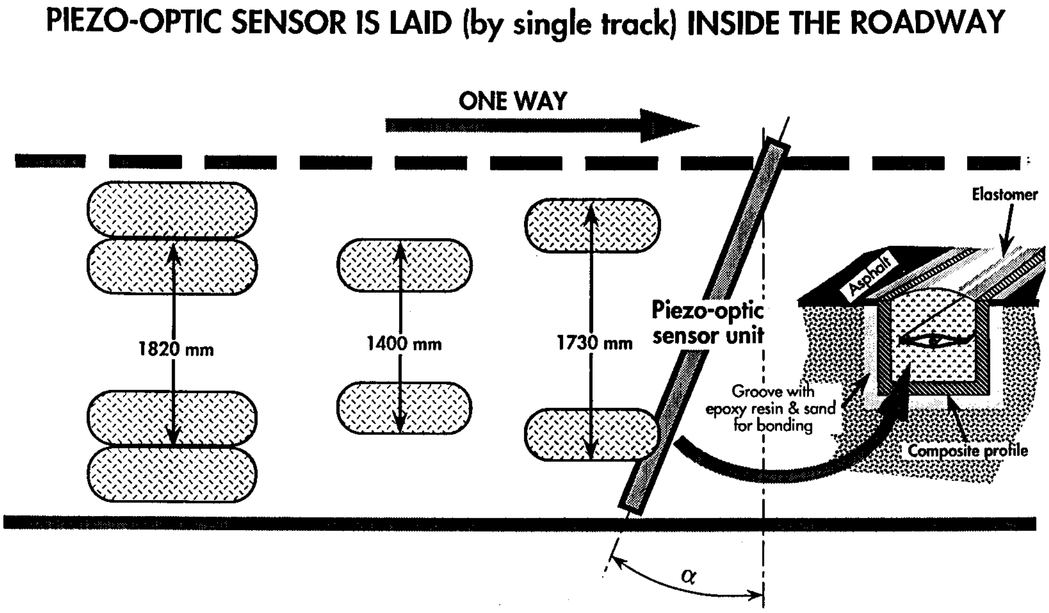


Figure 6 : Piezo-optic sensor is laid (by single track) inside the roadway

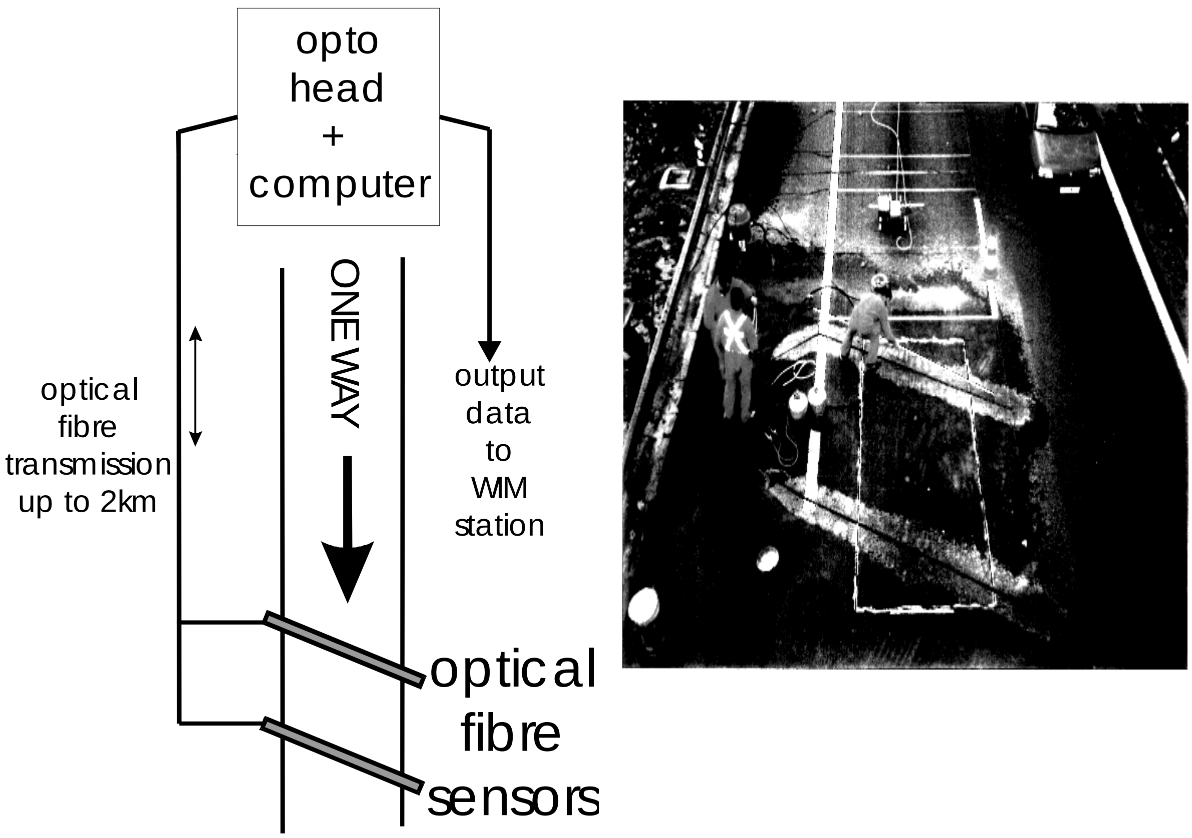


Figure 7 : Sensors installation on site

3.2 Opto-electronic head

An opto-electronic head includes (Figure 8):

- a 1330 nm laser with its driver,
- 2 photodiodes with 2 electronic amplifiers,
- an optical coupler, 2 light polarization filters.

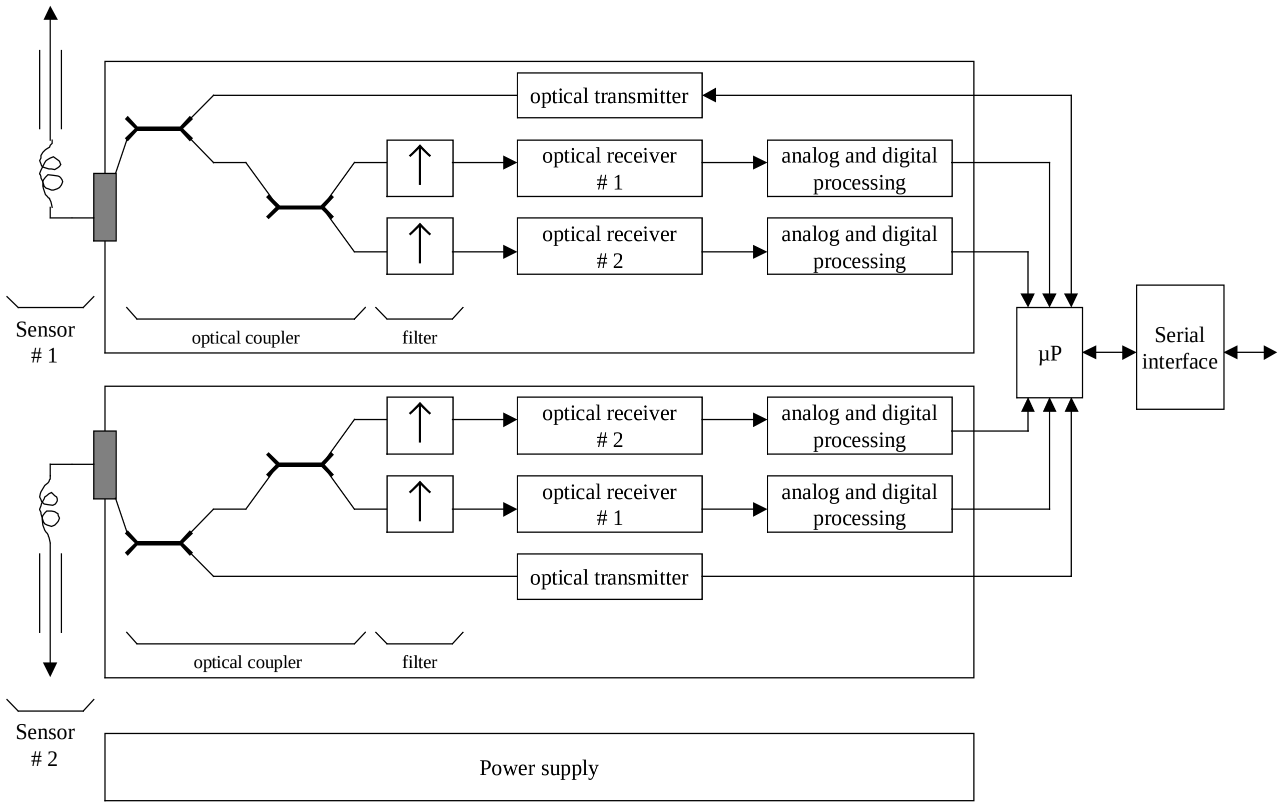


Figure 8 : Scheme of WIM optoelectronic head

The 4 electronic signals given by opto-electronic head are connected to a data acquisition module which digitizes 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 : to record measurements ; to compute weights, speeds and to show signals and results. One elementary opto-head is able to manage two sensors, as showed (Figure 8). Extension to multiple sensor WIM is illustrated (Figure 9). We can note that optical link between each sensor and optoelectronic head is able to reach up to one or two kilometers. Option was developed allowing to connect itself with communication optical fibres generally located along roads to transmit various data.

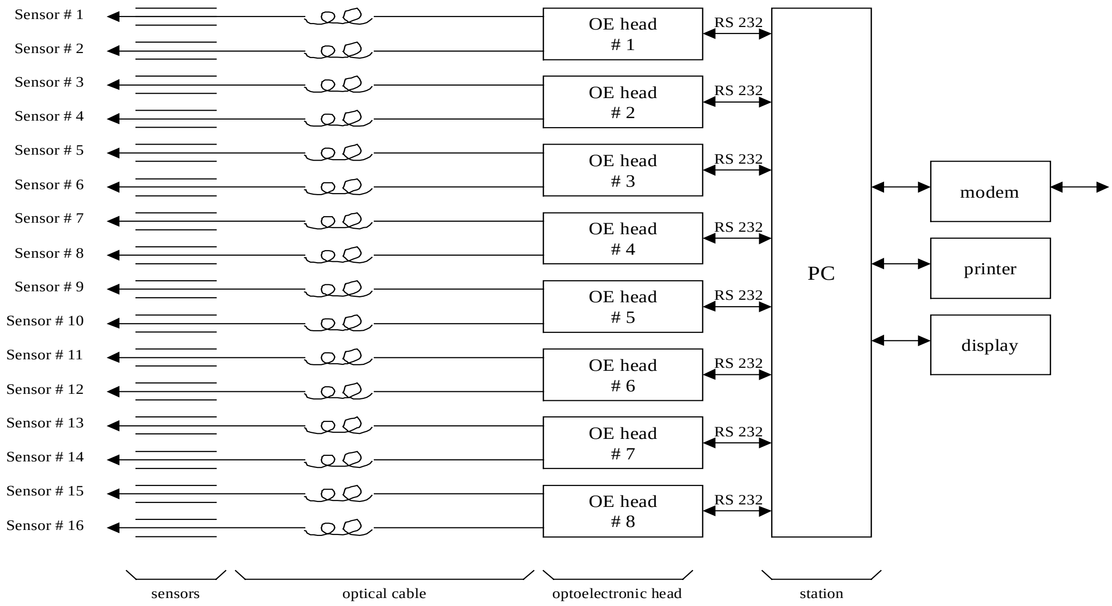


Figure 9 : Scheme of Multiple Sensor WIM station

3.3 **Software functions**

Within the WAVE WP 4, the AML company, a sub-contractor of Alcatel worked on the following subjects :

- configuration, geometry of the sensors in the road,
- choice of the electronic acquisition system : resolution, bandwidth, frequency of sampling,
- size of memory, convenient software,
- during sensors test in laboratory, at Clichy, we observed folded fringes which make impossible further processing. AML studied this problem, and wrote a filter software, well fitted to these real signals, so measurements in laboratory went on.
- Analysis of recorded signals, specification of the treatment software , choice of the most efficient processing principle when some noise is added to the measured signals.

The software reads 2 measurement series, sine and cosine, for each sensor, it finds the start and the end of each wheel, it computes the phase of the optical signal coming from the sensor.

Using data from 2 sensors, the software calculates the wheel speed, the force applied by the wheel to the ground, the distance between two wheels, the vehicle weight.
Then the software writes results in a output file, and displays results.

4. **SENSOR CHARACTERIZATION**

All sensors are calibrated with a pressing machine at laboratory, before putting them into road site. Calibration aims at both checking a spatial homogeneity of the sensor response and its metrological performances determining : range, accuracy, resolution, ... To carry out tests, various forces from 1 up to 5kN, are applied by an incremental procedure to a sensor limited zone of 100mm long. All measurements are repeated every 100mm over a 2.70m current length of the sensor. It does about 30 loading cycles a sensor, because a small « dead zone » exists at each end of the sensitive bar. The load applying surface by testing machine corresponds to a 100x20mm rectangular area. Experimental results are shown (see Figures 10, 11). Sensor response has been normalized to be able to perform comparisons between both sensors and various sensitive areas for a same sensor. N/Cycle is the unit used.

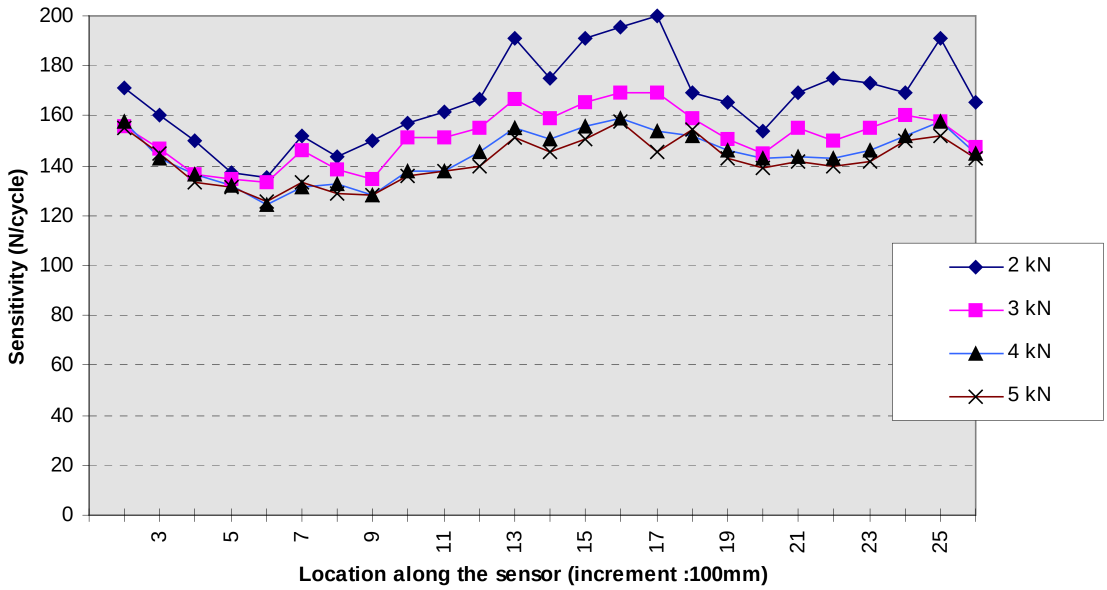


Figure 10 : Calibration of a first generation sensor

We can note that the measurement accuracy depends on loading level. This can be explained for low loads, the fibre delivers few polarimetric fringes. Consequently, the relative error on the weight calculation is higher. With normal treatment which computes at least four points a fringe enables to increase accuracy by a factor two. According to the location along the sensor, sensitivity is better than 10%. On the contrary, for higher loads, accuracy becomes better than 7.5 %. Mean loads that we chose, are similar to a force induced by a heavy truck axle.

A second experiment aimed at testing repeatibility of sensor response. To do it, we took 3 load levels : 1 kN, 3 kN, 5 kN and we selected five limited areas of the sensor out of thirty (see above) to apply the loading. Testing sequence is repeated 10 times.

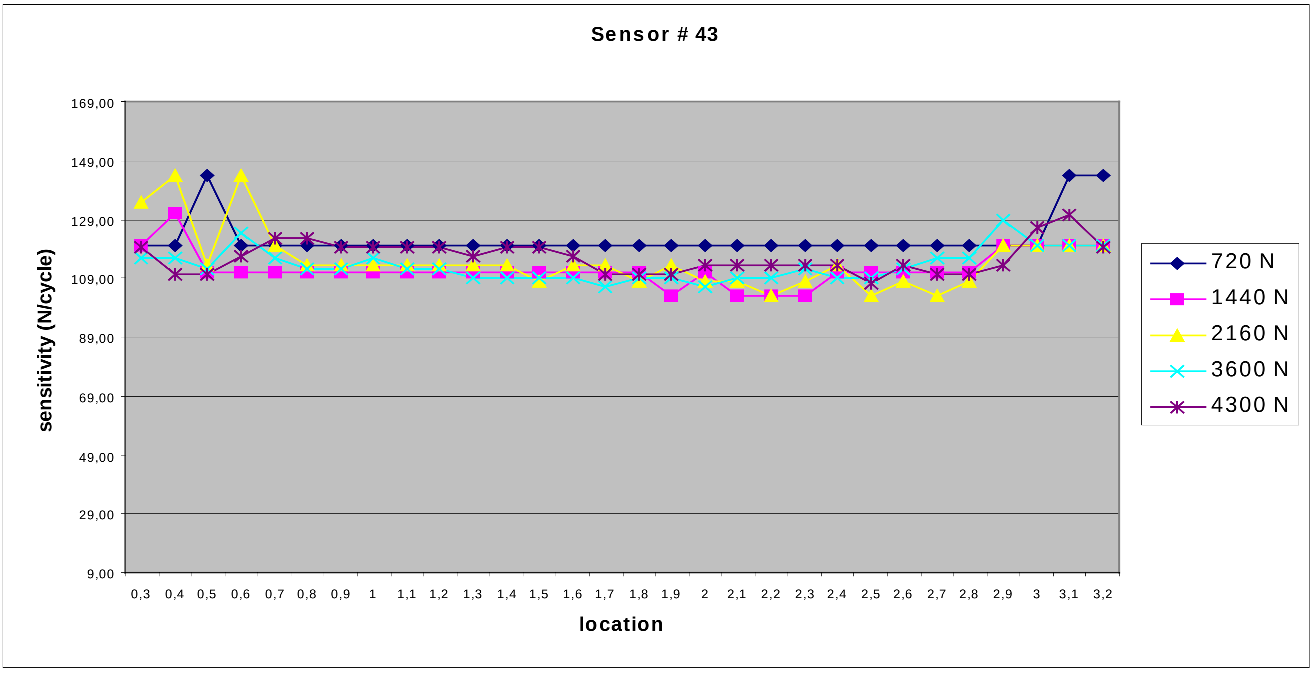


Figure 11 : Calibration curve of the sensor # 43 - (last generation of sensors)

We can see by comparing (Figures 10 and 11), quality improvement in making between the first and last generation of sensors, allowed to get a best spatial homogeneity of sensor response

5. FIELD MEASUREMENT

5.1 RN 10 site near Trappes (France)

- Since December 1995, two sensors were laid on RN 10 site near Trappes (France). The way presents a traffic about 10.000 vehicules a day. In parallel on the site, several other types of sensors are operating : piezo-electric sensors, electromagnetic curls, ...

For the experiment, we note that the two attached sensors to the road for two years of operating, have kept initial performances and a satisfying behaviour under heavy traffic and various weather conditions. It confirms that on, one hand, the choosen sensor design with sensitive element embedded in an elastomer material and located at the bottom of a U profile made of silica fibre, and on the other hand, the using of an epoxy resin to fix sensor within slab pavement, constitute a good compromise for metrological long-term performance maintaining

5.2 The Alcatel measurement place at Saintes (France)

Two 3.7 m optical sensors and a 1.5 m sensor were laid on the Alcatel plant by november 1998. In order to easily test acquisition system and to develop the processing software.
The two strip sensors are parallel and 1.5 m distant. Each sensor is linked to its opto-electronic head with 2 optical fibres.

Figure 12 : Experimental Alcatel site

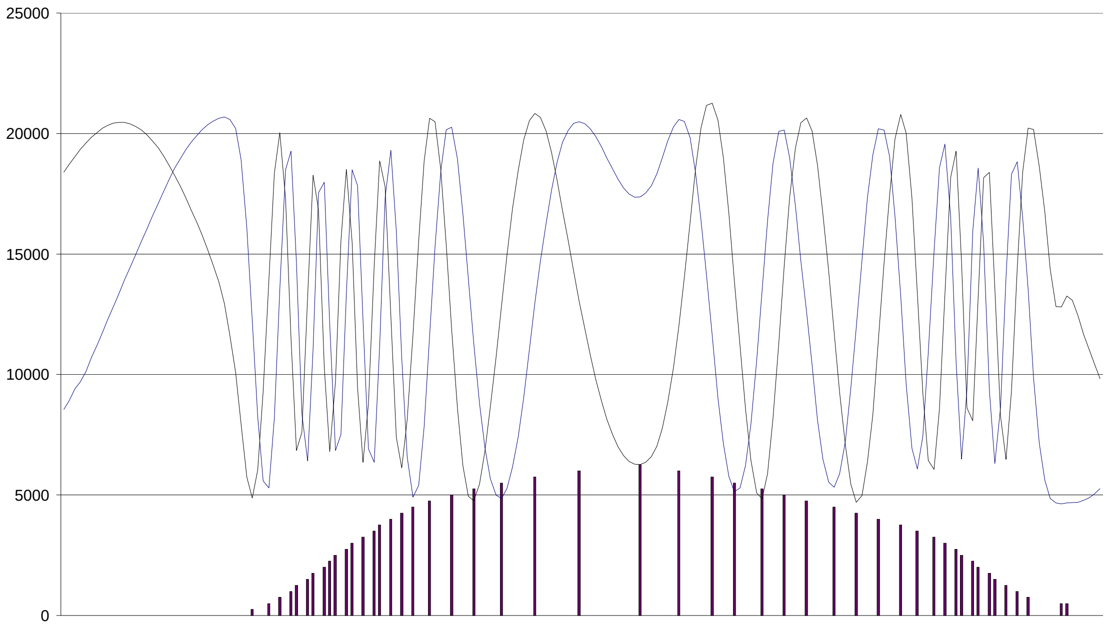


Figure 13 : a car wheel

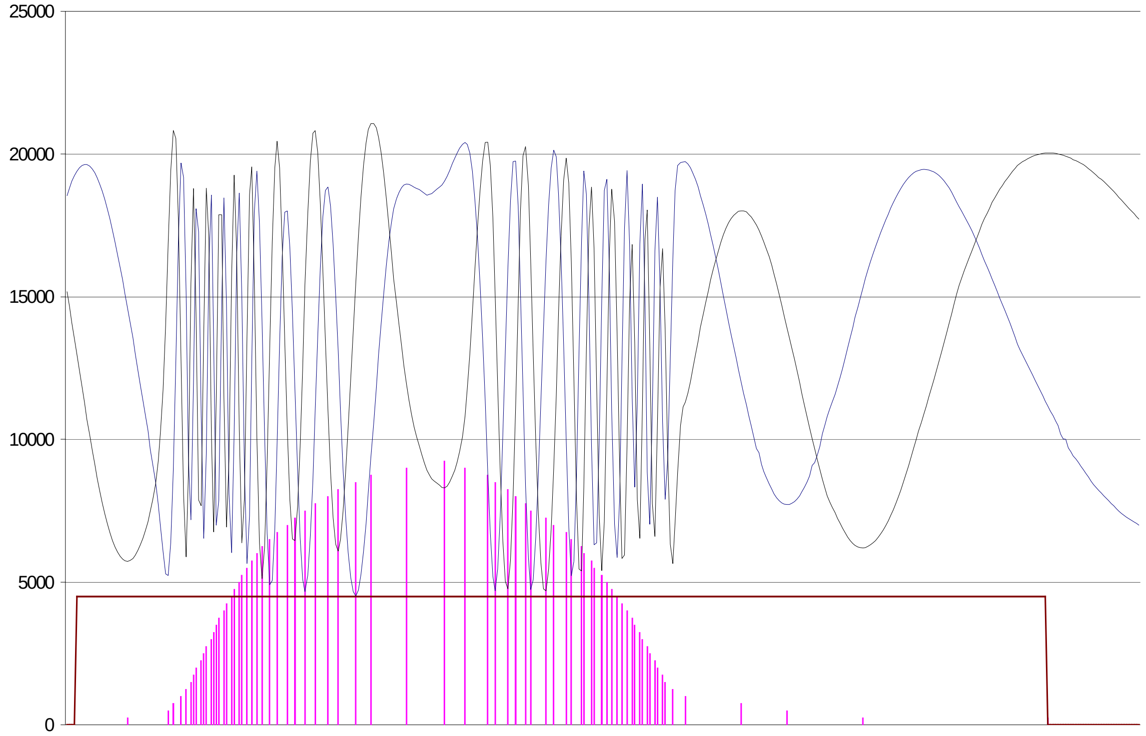


Figure 14 : a van wheel – load reconstruction

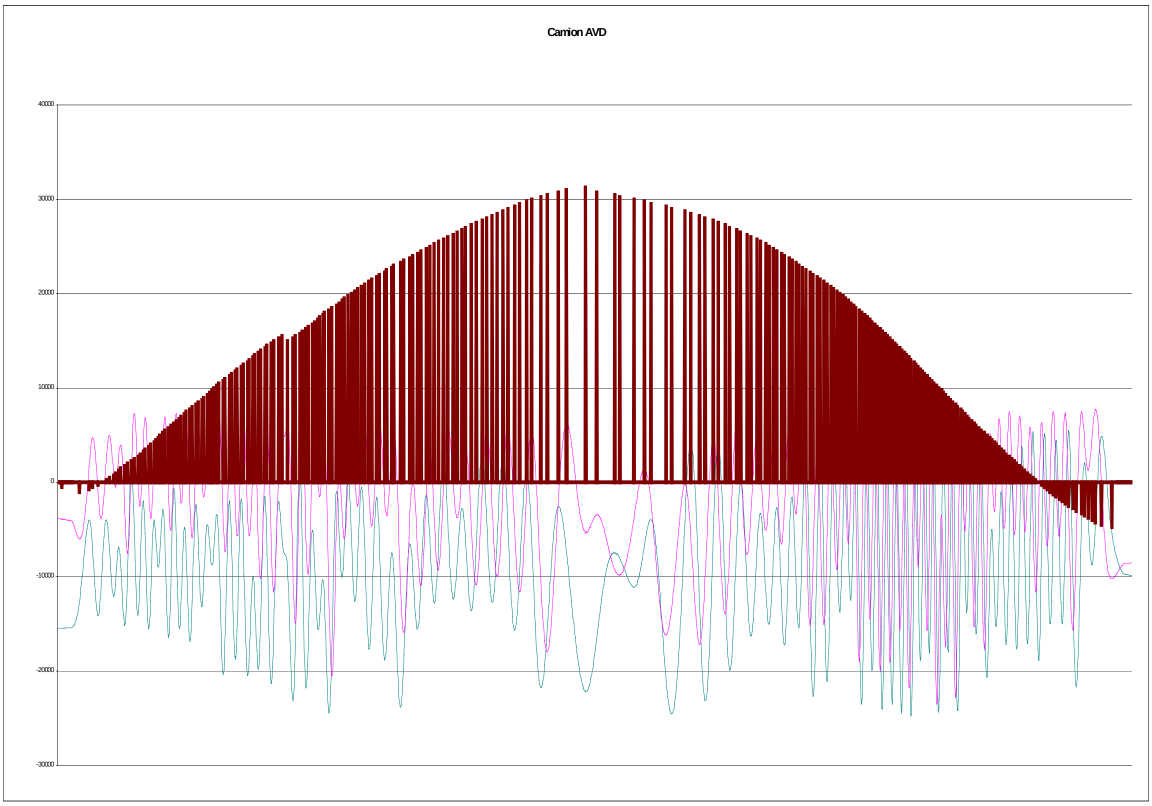


Figure 15 : a truck wheel – load reconstruction

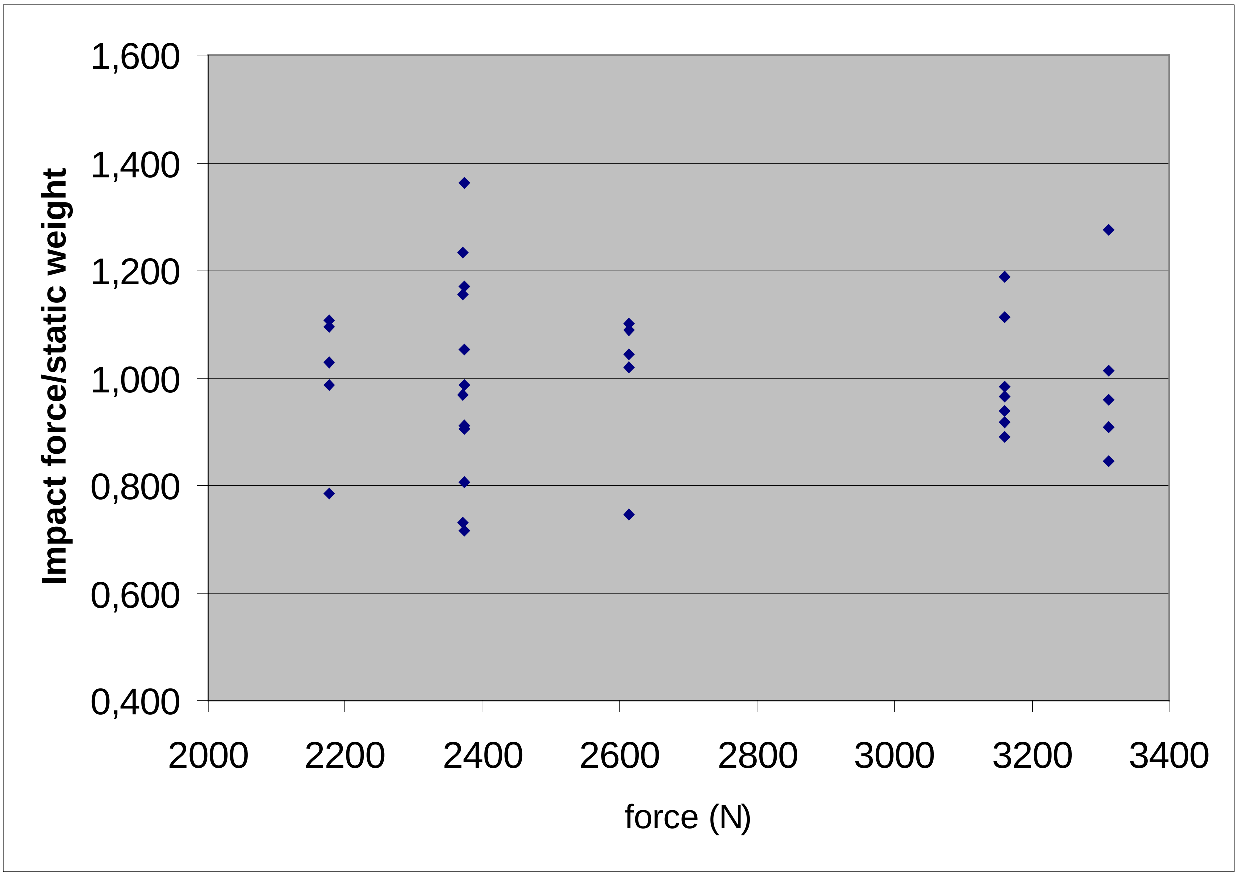
The two observed periodic functions on the same graph (Figures 13 and 14) show signals given by two optical receivers linked to sensor output according to two polarization directions. The bar curve provides the instantaneous strength reconstruction received by the sensor.
The strength computation is carried out on 70 points for the car wheel, and up to 200 points for the truck wheel, these point numbers are large enough to achieve the accurate shape of the impact force curve .
This impact force curve is a more wealthy information than results given by other sensor technologies.
Figures (14) and (15) show the tiny ground motion before and after the wheel runs over the sensor.

6. EXPERIMENTAL RESULTS

Measurements carried out on a parking lot, at Saintes, with vehicles, whom speed was between 10 and 15 km/h, are showed (Figure 16). Y axis indicates the ratio measured impact force/ static weight. The X axis indicates the static weight on the wheel.

During the calibration procedure, we observed a large result dispersion. The main cause of this dispersion is the degradation of the ground level. At the end of the winter, level differences reach +/- 15 mm, which causes random motions of vehicle suspension : left to right, front to rear. We reduced the dispersion checking more accurately the location of tyre print on the sensors. The poor quality of the ground site hides intrinsic accuracy of sensors, observed during calibration.

Figure 16 : Comparison between impact force and static weight for a given force



More, we can note that resolution is not dependent of the total load. Its value, 30N, corresponds to the quarter of a fringe. This is obtained by the aid of both extreme sensor sensitivity and treatment. Now, for a car wheel absolute error is ± 300N. It is a very weak value. If we combine static weight error and absolute error in field conditions, we can expect good relative accuracy for heavy loads. For these loads, accuracy becomes better than 5 %. Mean loads that we chose, are similar to a force induced by a heavy truck wheel.

7. OPERATIONAL LIMITS

They have to be chosen so as to meet the most severe conditions. Considering for instance limit values :

- tyre footprint length : 0.5 m ; half-axle weight : 7000 kg ; maximum speed : 35 m/s (i.e : 126 km/h)

the following orders of magnitude are obtained :

- T : sensor crossing durations : 5 to 80 ms ;
- M : number of fringes : 3 to 300
- F : average fringe frequency : 30kHz ;
- $f_{\phi m}$: maximum fringe frequency (for a typical bell shaped load profile) : 60 kHz

To achieve a good quality of the fringe treatment, the sampling frequency has to be selected in order to get 10 samples per period. As a result, the range of the sampling frequency will be between 50 kHz, for weighing at 10 km/h, and 500 kHz at 100 km/h, but the number of recorded samples during a run will always remain moderate (e.g. less than 10000) with a fitted sampling.

8. MAIN FEATURES OF OPTICAL FIBRE WIM

From the above results we can extract main characteristics of the weigh-in-motion by using optical fibre technique :

- good metrological accuracy and low temperature dependence,
- optical WIM can operate in both static and high speed conditions : full accuracy is guaranteed from a vehicle speed as low as 1 m/s and higher than 40 m/s,
- electromagnetic immunity : sensors and cables may be laid near high voltage lines and railways,
- time-saving installation : sensor is a glass fibre bar with a section 23x23 mm, 3,7 m long. The installation needs no more precautions than with the other WIM technologies,
- electric power is not necessary along the roadway, distance between sensors and optoelectronic head can reach up to 2km,
- a further process is being developed will be able to provide more relevant information from wealthy signals : tyre pressure, vehicle speeding up, dynamic effects ...,
- data processing performed in real-time,
- well-suited method to be connected with an optical bus and with a network.

9. CONCLUSION

Wave programme enables us to :

- improve the optical sensor technology : shape, elastomer, manufactoring, and testing,
- achieve an opto-electronic converter reliable, well fitted to the sensor requirements,
- study the processing principles,with the help of the AML company,
- implement and test the software treatment.

Temporary results, got in laboratory show :

- The sensor sensitivity (120 N/cycle), the accuracy of the impact force measurement,
- The capability to operate in static conditions, and at a high speed as well.

Field tests point out :

- An easy installation, like other strip sensor,
- The wealth of recorded signals which will enable to reach other parameters like : tyre pressure estimation, vehicle acceleration while measurement, or warning against worn out suspension.

New sensors are on process of manufacturing, the sensor installation in highway is scheduled on Q4 99.

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Patents

[P1] *Jauge de pression à fibres optiques,*
French patent N° 88 02 765

[P2] *Procédé d'obtention d'un capteur à fibre optique précontrainte et son dispositif de mise en œuvre,*
French patent N° 92 00 952, folio 18925

[P3] *Piezo-optical pressure sensor,*
German patent N° 42 36 742 (KE 9246)

11. DELIVERABLES OF WP4

11.1 WIM by using optical fibre technology

Sensor
Optoelectronic head
Hardware and software for data recording and processing
WIM system for managing two sensors

11.2 Progress reports

PR1, PR2, PR3, PR4, PR5, PR6, PR7, PR8
Presentation of papers at Zürich, Lisbon and Paris European Conferences

11.3 Tasks not performed

Experiment on site at Metz and Lulea (CET tests and cold climate sensor tests)
Long-term performances of sensors
Mutiple-sensor WIM