A High Performance WIM System by Piezo-Electric Cables and Its Application

Bernard Jacob[1] **Marcel Siffert**[1]

ABSTRACT

The need to know the traffic on a highway system arises from regulation, economic, and technical considerations.

Knowledge of the volume of traffic, and most important of all of the actual loads transported and applied to the pavements, serves to check compliance with rules of safety and fair competition (regulation aspect), to determine indicators of the economic life of a country or region (economic aspect), and to guide the structural and geometric design of pavements and engineering structures (technical aspect). It is in the area of the structural design of pavements and engineering structures that the lack of precise data concerning the true applied loads is most acutely felt. This is the fundamental parameter of design and maintenance methods that is the least accurately known.

Most structural design methods make use of the concept of traffic-induced fatigue, in the form of the extent of damage by loads or of the total number of standard axles in a specified service life. These methods are generally based on the few load histograms available and make use of sometimes debatable statistical relationships between heavy trucks defined in administrative terms (e.g., trucks over 5 tons payload) or total traffic volume and the real loads applied to the pavements. This situation is explained by the means hitherto available and used for traffic determinations: either simple and inexpensive devices (air hoses, inductive loops) that yield an approximate idea of the volume of traffic but no information about the loads transported, or static or dynamic weighing apparatus that is so expensive to purchase, install, and maintain that only a few dozen at best can be used in any one country.

The work done in France to obtain a better knowledge of heavy traffic and apply it to the design of pavements and engineering structures has proceeded in two stages. The first, from 1968 to 1976, consisted of installing and operating, at about 50 locations on the national highway network, dynamic weighing apparatus used to establish a first histogram of the distribution of the loads transported. These data were combined with the results of checks of the loads of commercial vehicles available from other sources (static weighings) to establish more or less consistent "traffic" input data for our design methods. The second stage, begun in 1975, has involved:

- carrying out a synthesis and a critical analysis of the available information;
- analyzing the traffic knowledge needs stated by the administrators of various works (engineering structures, motorways, national highways, secondary roads, and so on);
- carrying out an exhaustive study of many physical means and principles and of devices in existence or under development;
- developing to the operational stage simple, low-cost means of classifying loads that could be used extensively on main and secondary roads;
- developing a structural design method based on the true degree of damage resulting from the applied loads.

The development of these new simple and low-cost means of classifying loads required many theoretical and experimental investigations. They are coaxial cables of the piezo-ceramic and piezo-polymer types, sensitive to a unit derived from mass (pressure - strain), that by suitable electronic processing of the signal yield a sufficiently accurate indication of the loads of axles and vehicles. The many verifications in test tracks, structural fatigue testing merry-go-rounds, and

1 Ministère de l'Urbanisme, du Logement et des Transports, France

more than a hundred actual roads have made possible the development of a sensor that is highly selective with respect to the applied vertical loads; moreover, production and certification quality control procedures are being developed to ensure that the product will meet users' requirements. Many comparisons have also been made with static and dynamic weighing apparatus, under a variety of conditions, and the results are satisfactory. Since 1985, an "industrialized" product has been available, together with its associated recording systems:

- load histogram recorder, programmable by microprocessor to allow for the setting of the number, thresholds, and intervals of the load classes, with battery power supply;

- fine traffic analysis station with built-in microcomputer allowing for a very fine analysis of the composition of the traffic and of various parameters (volumes, loads, speeds, heavy truck silhouettes, etc.)

The paper describes the items of equipment used and their capabilities (life, precision, etc.), together with the various types of operation available for the analysis of loads and a number of significant results concerning the actual distribution of traffic from the viewpoint of degree of damage to pavements.

Finally, a method of taking the actual degree of damage by traffic loads into account in pavement design and maintenance methods is proposed. Such results are also required for bridge design and maintenance, and codes calibration. Calculations of load effects have been made from the traffic data recorded and the influence lines of some bridges and fatigue damages or extreme values were computed.

INTRODUCTION

The knowledge of the traffic carried by a highway network is needed for the enforcement of regulations and for economical and technical reasons.

The volume of the traffic and the load actually transported contribute to determining the indications of the economic life level of an area or a country.

The loads applied to the pavements and the bridges or other structures provide major information for the geometrical and structural design, for the code calibration and the structures maintenance or repair.

More precisely, most of the pavement design methods use the notion of traffic induced fatigue, translated into terms of the aggressiveness of the loads or the total number of standard axles for a specified service life (2) (8). For the bridge design a complete knowledge of the traffic loads, in terms of axles and vehicle weights, spacing between axles and trucks or speeds is required for a large number of vehicles and a long time period of traffic.

The classical device for the static or dynamic weighing as the plates developed until now are so expensive (purchase, installation and maintenance) that most of the countries are now looking for new technologies offering low cost weigh-in-motion systems.

The French Administration (Ministry of Housing and Transportation) has first undertaken and developed a major research program to obtain a simple, discrete and inexpensive system with wide use possibilities.

Since 1978, the french "Vibracoax" ceramic piezoelectric cable, patented in 1976 by the company Thermocoax (Suresnes) (3) has been studied and then adopted following a rigorous study of many physical principles and processes and many extensive investigations and testing for building a cheap and high performance sensor of axle loads (1) (11). Such a sensor and the connected electronic system allow to record automatically very large samples of vehicles on one or more lanes, providing the statistical data for all the mentioned applications. Since 1982-83 some other countries appeared to be interested in this technology and bought such a system or conducted similar research works.

This paper presents the current performance and applications of this product.

THE PIEZOELECTRIC TRAFFIC LOAD SENSOR

PHYSICAL DESCRIPTION OF THE CABLE

The main part of the sensor is a coaxial 3 mm diameter cable with metallic copper inner and outer conductors separated by a piezoelectric ceramic under compressed powder form.

Manufacturing
The cables are made by drawing the various constituents together; when the drawing operation has been completed, the cables are polarized by applying a strong electric field at a temperature close to the Curie point of the ceramic maintaining the electric field while the ceramic is cooled. The electrodes used to create this field are the inner and outer conductors of the cable. The result is a radial field depending on the relative dimensions of the cable and on the applied voltage (3). The cable is delivered at the proper length connected with a coaxial connection cable.

Principle
Whenever a mechanical stress (pressure, shock, vibrations, bending, twisting, etc.) is applied to the cable, an electric signal appears between the inner and outer conductors. The cable therefore has applications in many fields, provided that it can be made to respond selectively to the value to be measured; for example, for an accurate pressure measurement, shocks, vibration, twisting, etc. likely to disturb the signal must be eliminated.

If a pressure variation P is applied over a length 1 of a cable of a length L, it results in a voltage between the inner and outer conductors given by:

$$V = K.\ P.\ \frac{l}{L}.F$$

where:

$$F = \frac{C}{C + Cm}\ e^{-t/T}$$

- l is the length of cable to which the stress is applied (width of tire imprint)
- L is the total active length of the cable
- P is the pressure variation applied over l
- K is the coefficient (constant) characterizing the sensitivity of the sensor
- C and Cm are the capacitances of the sensor and of the associated measurement circuit, respectively
- T is the time constant of the circuit.

The operating temperature range with no loss of sensitivity is comprised between - 50 and + 80° C. The sensitivity of this cable is 10^{-4} V/N/ m2 with a capacity of 6000 pF/m, a minimal isolation resistance of $10^{-10}\Omega$. One end of the cable is terminated by a sealed cap that maintains the insulation between the inner and outer conductors; the other end is connected either directly or via another coaxial cable to a measuring instrument, generally having a low input impedance and a long time constant.

Testing and Qualification
Tests are made by the manufacturer in the factory as well as before use of the cable in order to check its reliability and performance. Its composition, electrical insulation, sensitivity, homogeneity ... are checked by the inspection procedure. An official qualification procedure (10) has been developed. Some specific devices are now operating such tests, like a pressure box.

DEVELOPMENT OF A DYNAMIC LOAD SENSOR

The cable alone is able to detect the presence or absence of a signal when axle or vehicle passes are detected. The applications of this operating mode, of particular relevance to pavement safety and geometry are:

- the detection and counting of vehicle axles; the sensitivity in such that two-wheeled vehicles (bicycles, motorcycles, and the like) can be detected;
- measurement of instantaneous and average speeds, using two cables
- measurement of distances between axles and times between vehicles;
- measurement of vehicle widths;
- transverse position of the vehicle on the lane or pavement;
- traffic monitoring and control (traffic lights, car parks, toll stations, infringements, etc.);
- restitution of silhouettes, evaluation of the lengths of heavy trucks.

The applications, which do not concern weight, are mentioned here only because they very often provide additional information that is helpful to persons in charge of highway operations and safety when combined with weight data (e.g., relations between loads and speeds, studies of silhouettes, speeds, loads, etc. of heavy trucks). They are less demanding in terms of sensor quality and conditioning, sensor installation and signal processing.

In the foregoing applications, this sensor may already be compared favorably to more conventional systems (inductive loops, pneumatic interference. But in the area of load evaluation its advantage becomes decisive (1).

Principles of the Load Sensor and Studies

A load sensor can be made by taking a sensor sensitive only to the tire-pavement contact pressure and determining the product of this value by the tire contact area. So far, none of the various arrangements of the cables on the pavement surface has lasted more than a few months: the slightest loose patch results in vibrations or twisting effects that disturb the signal.

To ensure a life of many years, the sensor and its jacket are placed in a groove; in this case, the stresses induced in the sensor no longer result exclusively from the vertical component related to the axle load.

A theoretical study was conducted to evaluate the various factors likely to influence the operation of the cable, to determine the stress levels, and to obtain a sensor sensitive only to the vertical load applied by the tire.

This involved:

- the calculation of the stresses at a given point in the structure,
- a local study in the vicinity of the sensor with analysis of the perturbation introduced by the sensor into the stress field calculated by the foregoing global study,
- an evaluation of the radial pressure on the jacket of the sensor, a calculation of the values and directions of the principal stresses,
- an estimate, based on the foregoing calculations, of the excitation of the sensor at a given time,
- evaluation of the total signal typical of the sensor-load-pavement system, when a load passes.

The following parameters have been mastered to obtain a sufficiently precise and reliable sensor and its conditioning: sensitivity to vibrations, torsion, longitudinal tensile stresses and transverse bending stresses, decoupling of the sensor from the pavement with respect to the horizontal stresses and influence of the temperature, and of the vehicle speed.

The LCPC's Sensor

The final product of this research and of many field tests in the so called "LCPC's sensor", a ready to be installed bar consisting in a piezoelectric cable embedded in a resin having a temperature independent modulus and ensuring proper transmission of the vertical stresses. The selectivity for the stresses representative of the load is higher than 95%.

The effects of longitudinal torsional stresses and transverse bending stresses are attenuated both by stiffening the bar by the way of a metal channel and by placing rubber strips having a very low modulus along the sides of the bar.

For a vehicle of a given load, the signal amplitude is constant for all speeds thanks to a very-high-impedance amplifier.

The calculation results and experimental verifications have made it possible to develop and optimize the sensor and the installation method; studies of resins have lead to the development of a product that satisfies the above-mentioned conditions and at the same time ensures very good bonding to various pavement materials and rapid installation. This sensor is patented by the LCPC.

Tests and Calibration In Situ

The bar undergoes an examination similar to the cable tests for sensitivity and homogeneity. After the installation in the groove of the pavement further tests are done for accepting the installation and calibrating the sensor, by a mobile impact apparatus, acting on the same zones and under the same conditions as the above-mentioned checks or by trucks having known axle weights, driven at various speeds.

Additional experimentation has been done by other means:

- vibration bench (known forces are applied to the sensor at known frequencies);
- traffic simulator (the sensor is subjected to alternating loading cycles at varied pressures, loadings, and temperatures);

- the LCPC circular fatigue test track (repeatable tests of reliability and temperature stability);
- observation on actual pavements (at approximately 200 sites).

An original method of automatic permanent calibration is developed in France on some sites using the characteristics of special trucks. The statistical data have shown that the first axle of the four axle half-trailers have a low scattered load around 4.5 to 5 tons and in case of a gross weight more than 30 tons, the second axle is very close to 12 tons. The system is on time self calibrated by fitting the moving average of such axle loads on this particular value. It provides a very easy and efficient calibration for the permanent measurement over long periods.

THE ASSOCIATED ELECTRONICS

Processing of the Signal

The electric signal delivered by the sensor must be processed. Depending on the application, two levels of precision are defined.

- *Precision 1*:
  This is provided by electronics consisting of a very-high-impedance amplifier, a pavement flexion compensating device, and an output amplifier-detector. This simplified equipment is based on the principle that, as a first approximation, the product P x 1 (contact pressure tire imprint width) is directly proportional to the axle loading.

  The precision is approximately 18% in comparison with the static weight.

- *Precision 2*:
  This calls for a second cable at a distance D from the first, making it possible to measure the speed of the vehicle. This yields a more precise determination of the load by the product of the pressure by the tire contact area.

  For precision reasons a system of integration is added which gives the same quality as the traditional plates.

The Electronic Systems for Data Recording and Processing

This equipment was developed further to a study of the requirements and applications in France and in developing countries. There are four categories depending on the precision of the load knowledge; within each category, options allowed for the simultaneous recording of speeds, traffic flows, intervehicular times, etc.:

- The CV 80 counter counts the vehicles that exceed its adjustable load threshold. It works with one single sensor.
- For histograms, the PE 16 counts all vehicles and sorts them into five axle weight categories ranging from 1 to 13 tons; with the Ap 16, the number of weight classes is programmable (up to 20) and the thresholds and class intervals are adjustable thanks to a built-in microprocessor.
- Both work with one single sensor and the precision 1 level.
- Standard traffic analysis stations have been operating since 1985. They yield a classification into five weight categories (histograms), with information about traffic flow speeds, spacing etc... They are built with microprocessors and work with one sensor associated with a magnetic loop.
- Precise traffic analysis stations (SAFT16) provide information about traffic either by weight category (sophisticated histograms) or in the form of the actual weight in tons. It includes a built-in calibration and testing device and a microcomputer used for data acquisition, real-time monitoring and processing. The associated software allows to record and determine most of the characteristic traffic parameters: axles and vehicle weight and spacing one by one, speeds, time of passage, etc... An example is the restitution of heavy truck profiles in 13 categories (which cover 97% of the heavy trucks on French roads), together with weight and speed information. They are working with two sensors eventually associated with a magnetic loop in case of traffic jams and the precision 2 level. Five stations of this type have been used on motorways, national highways, and local roads for three years.

Performance and Experimental Results

The 200 cables - among which 50 date back more than five years - installed in France, have yielded a substantial quantity of experimental results;

they bear out the hopes placed in the development of this product, at least for the climatic conditions and pavement structures found in France. Precision levels 1 and 2, mentioned previously, may be defined as follows for a sensor properly installed in a pavement having good evenness:

- for level 1, 90% of heavy-truck weight measurements are within 15% of the static weight;
- for level 2, 90% of heavy-truck weight measurements are within 10% of the static weight.

(results obtained with more than 200 trucks).

These ranges include the influence of dynamic effects, which become very large with pavements of mediocre or poor evenness.

There have been many comparisons, in France, of static weighing and dynamic weighing by piezoelectric cables, at different locations and different times of the year. The results confirm that the performance of the sensors is satisfactory for the planned applications.

APPLICATIONS IN THE FIELD OF ROAD TRAFFIC AND PAVEMENT MAINTENANCE

SCREENING OF OVERLOADED VEHICLES — MAKING CHECKS MORE EFFECTIVE

Campaigns checking truck loads face many economic and technical difficulties: the cost of the equipment and manpower, the low mobility of the equipment, evasion by trucks (quickly informed by CB), and so on.

- Piezoelectric cables placed upstream of the inspection areas may be used to screen the vehicles and thus avoid wasting the time of non-offenders. Operations of this type in France in the last three years have raised the average efficiency of the checks (number of offenders as percentage of the total number of vehicles stopped) from 35% to 95%.
- A network of 30 standard traffic analysis stations are in operation since 1986; these stations are located on the routes where inspections are customary. These stations are used to orientate inspection operations in time and space, by identifying the routes and times where violations are most frequent.

These two applications have resulted in a significant increase in the efficiency of the inspection operations, with no increase in the quantity of equipment or number of personnel used for these specialized missions.

CONTRIBUTION TO THE OPTIMIZATION OF PAVEMENT DESIGN AND MAINTENANCE

Almost all design and maintenance methods take the aggressiveness of the traffic (referred to a standard axle) into account (2); the pavement service life is estimated and maintenance operations are scheduled on the basis of an evaluation of the total traffic in number of standard axles and comparison with an admissible loading threshold determined from the fatigue properties of the pavement materials. The proper use of these methods and the correct fitting of the design model parameters depend on the precision and representativeness of the information concerning the loads a route bears.

The dispersion of the aggressiveness levels found on different types of roads reflects the weakness of the conventional methods of taking the traffic parameter into account (volume or percentage of heavy trucks).

APPLICATIONS FOR BRIDGE DESIGN AND MAINTENANCE

All the data for these purposes are provided by the SAFT16 precise stations.

STATISTICAL DESCRIPTION OF THE TRAFFIC LOAD

As mentioned previously, the knowledge of the traffic loads is very important for the bridge design and maintenance and the evaluation of the load effects. Large samples of vehicles are required for having a good model of fatigue damages and above all, of extreme loads. Such a quantity of data requires a statistical processing and presentation.

Vehicle and Axle Classification
All the recorded axles are then split into two classes:

- the individual axle is the whole set of axles weighed by the piezo cable

- the "group of axles" is the set of isolated axles, the tandem and the tridem, both considered as a unique load equal to the sum of the 2 or 3 axles of the group.

The vehicles are split into five classes following the OECD classification.

This classification gives some homogeneous distribution of gross weights. The traffic on one location or lane is partially characterized by the proportion of each class in the traffic flow as well as by the density of vehicles.

Loads Distribution
The axles and groups of axle loads are then presented in some histograms.

Similar histograms are given for the gross weights of the vehicles in each class. Some general remarks can be made concerning these distributions; the gross weight distribution of type 1 vehicles is a simple or double peak curve from 0 to a maximum of 130 KN and decreasing quickly over this value. The distribution of types 2 to 4 are mostly bimodal, especially for type 4 vehicles (half-trailers with tandem or tridem rear axles). For the type 5, the gross weights are widely scattered due to the many silhouettes of trucks. Such histograms show whether the legal limits are being exceeded. Probability density functions are then fitted on such histograms in order to get a probability model of traffic loads (6).

Speed and Distances Distribution
The speeds of the vehicles and the intervehicle distance are also presented in some histograms with very constant forms. The speeds generally have a gaussian distribution and the distances a gamma one.

This is confirmed by fitting the probabilistic distribution, as well as for the gross weight distribution.

Such a model gives the basis for any traffic load simulation by computer for checking the fatigue damages or the frequent bad configurations on any type of structure.

Load Effects Calculation from Recorded Data
The whole traffic record obtained from the SAFT associated with the experimental - measured by strain gauges - or the theoretical influence lines of any load effect on a bridge allows the calculation of the load effects time history. Such a calculation is made in the LCPC by the computer program "TRAMFUL" (4).

This program computes step by step the load effects corresponding to the selected influence lines by shifting the axles along the bridge in the same configuration as on the road.

The whole set of computed values represents the time history of the load effects. A suitable treatment of such results is the calculation of the cross level histograms or the rain flow one for the fatigue damage evaluation.

Additional calculations are sometimes done for evaluating the consequences of special load configuration, using the simulation as explained in the section 4.3.

APPLICATION TO THE BRIDGE DESIGN, CODE CALIBRATION AND FATIGUE

Some results and interpretations for the bridges are presented hereafter:

- The influence line is the curve giving the intensity f(x) of a considered load effect for an axle of 1 ton at the abcisse x.

Code Calibration
The complete code calibration is a very important task much too long and complex to explain in detail here. Positive and negative maxima due to the uniform load of the French code corresponding to the serviceability limit states are compared with the maxima due to the real conditions of the traffic. The ratio of the limit state reached is presented, growing up to 95% for the bending moment of the central span under the Boulevard Peripherique's traffic. Some cases of overloading were found in other cases of bridges. Therefore, this serviceability limit state is now neglected and replaced by the ultimate limit state with an increase of 20% for the uniform load.

Fatigue Damages
An important study of the behaviour and the fatigue of the metallic orthotropic deck bridges under traffic load has been done for the European Steel and Coal Community (7) and further research work is now planned for defining the risk of cracking by repeated loads.

As described, the time history of the main stresses is computed from the recorded traffic data and the influence lines and a rain-flow histogram is done.

Then the well known Palmgreen Miner (7) model was used to compute the annual damage and the expected life time of the structure, with the help of the S.N. Woehler curves (stress intensity - number of cycles to the failure). Such results will allow in the future insertion in the new code some fatigue loads for the design. The simulation of traffic will be very useful for testing and calibration of these loads.

CONCLUSIONS

The French piezoelectric cable and electronic device WIM system has operated for more than 3 years in its final design and has been very successful for replacing the traditional plates with many advantages either technical or economical. A wide experience and application field is now accumulated providing all the required traffic and vehicle load data for the traffic knowledge, the pavements or structures design and maintenance, the new codes calibration, the management of the vehicles in the special area, etc.

The performances of the original LCPC's sensor as well as the associated electronic devices are in very good accordance with the requirements of the structures or pavements engineering and the accuracy of the system is sufficient in comparison with the deviation between the static and dynamic weights of the axles or vehicles proceeding on the real pavement surfaces. Thanks to the many data collected in France from five years, load effects and fatigue damages have been computed on many existing or future bridges, and the existing code is now under evaluation. Highway companies and other road network managers are also using this data for the pavement's maintenance or design.

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SESSION 5
COMMERCIAL VEHICLE ACCIDENTS AND SAFETY ISSUES

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A.M. Stevens
University of New Brunswick
Canada