Results of Weigh-in-Motion Project in France: 1989–1992

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A national research and development project began in France in early 1989 on weigh-in-motion (WIM) techniques and devices, under the leadership of the Laboratoire Central des Ponts et Chaussées. The objectives, organization, and main results of this project are presented; a new generation of WIM station recently developed by Electronique Contrôle Mesures within this project is described in detail; the application of WIM by a major French motorway company (Cofiroute) is explained; and some new concepts for the acceptance of WIM stations are discussed.

A weigh-in-motion (WIM) project was prepared during 1988 in response to expressed national needs. The Bridge, Road, and Transport Administration represented by its technical institutions [such as the Public Works Research Laboratories—Laboratoire Central des Ponts et Chaussées (LCPC) and its regional offices, LRPCs—and Service d'Etudes Technique des Routes et Autoroutes (SETRA)], the major motorway companies (including Cofiroute), and French manufacturers [including Electronique Contrôle Mesures (ECM)] had acquired some experience since the late 1970s, in vehicle WIM. These research works were developed for various purposes, such as pavement and bridge design and maintenance and statistical knowledge of traffic loads or enforcement.

After more than 14 years of development of WIM techniques using piezoelectric ceramic cables in France (*1–3*), it became useful to collect and compare the experiences of the various participants and to more fully consider the growing needs of the customers. It was also necessary to design and implement a new generation of WIM stations with the latest improvements in electronic computer hardware and software, and also signal processing of piezoelectric sensors. Therefore, it was intended to make the most of the experience acquired, to rationalize and coordinate research and development resources, and above all to bring all the participants together around common objectives by taking advantage of their complementary natures.

The project responds to three main demands of Public Works and Transport:

- Pavement design and maintenance on highway and motorway networks, revision of the pavement design code, knowledge of the aggressiveness of heavy traffic, and the provision of some tools to assist repair and maintenance policies;
- Bridge design and maintenance, including revision of existing bridge loading codes and the preparation of the new Eurocodes, the checking of some particular or exceptional projects, and fatigue studies for steel or composite bridges under traffic loads; and
- The survey and control of loads on roads to enforce the law, and the gathering of statistical data for economic and safety purposes.

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ORGANIZATION OF WIM PROJECT

The WIM project was conducted by the project manager of LCPC and the project assistant manager of LRPC in Trappes. The following organizations participated:

- Public works laboratories and technical centers (the Ministry of Transportation);
- Motorway companies: Cofiroute, Autoroutes du Sud de la France, and Union des Societés d'Autoroute à Pesage (USAP); and
- Manufacturers and private companies: ECM, Drouard (a company that installs sensors in the roads), and Alcatel.

The project was divided into five working groups, whose objectives follow:

- Working Group 1. Development of a new Hestia WIM station.
- Working Group 2. Research on piezoelectric sensors, resin, and installation techniques, signal processing, and calibration.
- Working Group 3. Multiple-sensor WIM system.
- Working Group 4. New types of WIM sensors and optic fibers.
- Working Group 5. Customer requirements and project evaluation.

The total budget is roughly 12 million FF ($1.00 U.S. = 5.88 FF, 1993) including more than 70 percent in personnel costs. Sixty percent of the budget is covered by the Ministry of Transport through the LCPC; the rest is funded directly by nongovernmental participants. Altogether, about 40 engineers and technicians are working part time on the project. The planned project lifetime is 4 to 5 years, and the project was completed in 1993.

RESULTS

The first results were presented in 1991 (*4*). The following are the main results obtained after 4 years:

Working Group 1

In the planning, design, and development of the new Hestia WIM station by ECM, the new station was built according to specifications prepared by the French administration in 1988. It satisfies the demands of the customers and takes advantage of the most recent developments in electronic computer hardware and software and experience in piezoelectric sensors and signal processing. Some tests have been made since 1990 with calibrated trucks and real traffic vehicles to finalize the Hestia station. Now more than 25 of these stations are in operation around the world. Additional technical details are given later.

Working Group 2

Significant improvements of the WIM technique by piezoelectric sensors were obtained up to now. A simple new algorithm was achieved for signal integration to improve accuracy and avoid some double- or triple-axle misdetection. An automatic self-calibration procedure was introduced by the Centre d'Etudes Technique de l'Equipement (CETE) de l'Est, using some characteristics of common heavy trucks, and was implemented in Hestia.

To optimize response quality and the durability of sensors in the pavement, studies and comparisons of various resins were made for mounting the sensor in the road. These studies led to sensor installation and calibration guidelines specific to the pavement properties (*5*). Quality-control tests of the sensors before and after specific to installation are also being developed.

Working Group 3

To reduce the variance of the measured axle loads and close the gap between the dynamic and static loads that are caused by pavement roughness and vehicle vibrations, a multiple-sensor WIM system was devised, using more than two sensors per lane. An advanced signal-processing technique based on a weighted linear regression and a learning set of vehicles was developed to combine the individual records of one axle on each sensor and to properly estimate the static load; this procedure was tested by simulation (*6*) and is now being tested on real roads.

Working Group 4

A new type of sensor with optic fibers may offer at a low cost a powerful WIM system and provide more information than existing sensors. A feasibility study was conducted with on-road testing and real vehicles, which showed the ability of such a system to measure axle loads with very good sensitivity. A cooperative effort with Alcatel-Cables is underway to develop a prototype of a new optical WIM system.

Working Group 5

The requirements of all WIM customers were collected, especially on data transmission and remote control of WIM stations. New devices were then adapted to make them compatible with existing data transmission systems.

Motorway companies have played a large part in the development and testing of the Hestia station. Recommendations for WIM location and suitable pavement characteristics for measurements with an acceptable or high standard of quality have been published (*7*).

A data base of traffic load data collected on all types of roads was created at LCPC in 1990. More than 150 traffic records over continuous periods between 1 and 8 weeks, recorded at more than 50 WIM locations since 1982, are already available. They contain altogether data on more than 2 million trucks.

SECOND GENERATION OF WIM SYSTEM: HESTIA

Layout of Sensors on Pavement

One induction loop and two LCPC-patented piezoelectric sensors (Type E) are mounted per traffic lane. They are laid out as shown in Figure 1.

General Presentation of Hestia Station

The basic design of the station was determined by three criteria, which since 1988 appear to be essential:

1. Use of one intelligent detector (DU) per traffic lane to collect the data relative to each vehicle;
2. Use of a central unit (UC) to manage all the intelligent detectors and process their data to provide information according to customer requirements (the UC also communicates with the outside); and
3. Use of a standard European format.

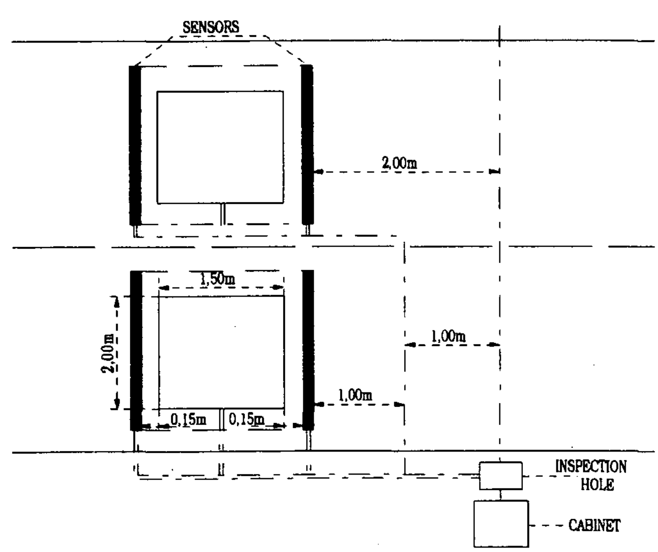

FIGURE 1 Installation of WIM station.

The structure of the Hestia station is shown in Figure 2. The Hestia DU detectors (2 and 4) receive the information from the piezoelectric sensors of Lanes A and B and from the loop detectors connected to the loops. In addition, each detector receives information termed anticoincidence from its right adjacent lane. Each detector is made of two cards: a four-layer digital card and a two-layer analog card. For each vehicle passing in Lane A, the Hestia DU detector provides all the information given in Table 1.

The system works by sampling during the induction loop detector switching time. The speed is derived from time T1 and the distance between the sensors. The distances between axles are calculated from the times T2, T3 . . . , and from the vehicle speed. The vehicle category is deduced from distances and weights. The RS232 serial link, the connector of which is located on the front panel, allows communication with the detector. The DU-UC dialog is carried out on the bus by break management with a system to avoid any data interference and to allow a very high throughput. Simulation trials carried out show that four vehicles, each having five axles, passing simultaneously on four different lanes, are handled by the system without any perceptible delay.

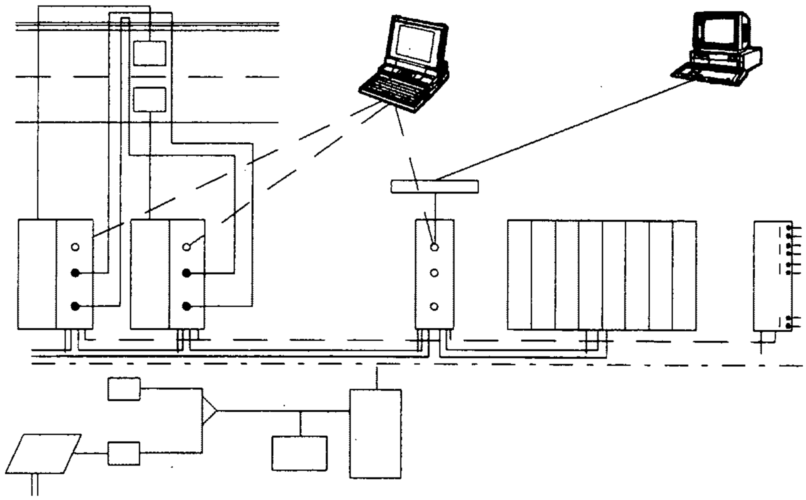

FIGURE 2 Design of Hestia.

TABLE 1 Output of Station

Measuring elements	Unit	WIM Detector WIM : AVC	Central Unit
date	d-m-y	O : O	X
hour	h-mn-s	O : O	X
choice of vehicle sensor	I/O	X : O	O
number of lanes	0 to 7	X : X	O
validation character	decimal	X : X	O
category	0099	X : X	O
speed (km/h)	mph	X : X	O
inter-vehicle time	ms or s	X : X	O
time spent on loop	ms	X : X	O
number of axles	decimal s 20	X : X	O
total weight	100 x lb 0.1 T	X : O	O
weight of each axle	100 x lb 0.1 T	X : O	O
inter-axle distance	ft : 100	X : X	O

The UC interacts with a maximum of eight lane detectors, with the external memories (7/1 to 7/8) made up of one to eight 1-megabyte (M) cards, backed up by lithium cells, with the Alarm card, and with the outside via the RS232 (or using 300- to 9600-baud modems). Only the UC has a battery-backed real-time clock. Each DU detector and the UC are driven by a 16-bit CMOS 80C186 microprocessor. This unit provides a visual display of the traffic in real time and statistics in four user formats, some of them compatible with Lotus 1-2-3. It also records, if needed, a file with the results vehicle by vehicle and lane by lane.

The power supply is provided by direct current (DC)/DC convertors (15) with electrical voltage decoupling and integrated smoothing from an 85-Ah load battery. The battery charger can be supplied by 220 or 115 V (50 or 60 Hz) mains or by an 880- × 445- × 36-mm solar panel.

The Hestia station is available in two versions: a double-cased fixed system for a maximum of eight traffic lanes and 8 M of memory, and a portable system for a maximum of two lanes and 5 M of memory. The station can be integrated into a traffic management network.

Signal Processing for Axle Load Calculation

Signal processing is carried out independently on each of the two piezoelectric sensors. It is therefore possible to compare the results obtained from each of the two sensors to determine whether the speed was correctly measured.

In addition, the use of two sensors improves the accuracy, either by averaging the two measurements or by selecting the more accurate sensor. Axle loads are computed with the help of the surface pulse produced during the passage of an axle.

Automatic Self-Calibration Algorithm

The original automatic self-calibration algorithm mentioned earlier provides at regular intervals the value that must be allocated to the unit square to calculate the integral of the signal produced by each axle. This value determines the axle loads. The areas used for the load calculation are first corrected for the vehicle speed.

The automatic self-calibration algorithm originates from a statistical study of vehicle parameters. In this study, it was pointed out that the first axles of some vehicles (termed characteristic) whose gross weight is above 30 T have a very low dispersion of the load around the mean of 6.1 T (on French national roads); in addition, the gross weights of these vehicles are centered on 40 T (other values may be determined for U.S. traffic). Then a weighted moving average of these parameters is continuously computed and fitted on the given target values to make the self calibration.

Station Initialization

Detector parameterizing is carried out from the RS232 serial link with the help of a PC/AT-compatible microcomputer, either from command words or from the user-definable ECoM software. The parameters to be defined are the distances between sensors, the choice of calibration method (testing vehicle or self calibration with its constants and target values), the sensor(s) used for weighing, and some additional choices, such as the loop size to measure the vehicle length.

EVALUATION OF TRUCK AGGRESSIVENESS ON MOTORWAY NETWORK

Presentation of Cofiroute and Utility of Weighing

Since 1970 Cofiroute, a private toll highway company, has been building and managing a network that spreads toward the western and central parts of France (Figure 3). In 1992 its network consisted of 732 km, making it the fourth longest in France. It is made up of four highways: A10 from Paris to Poitiers, A11 from Paris to Le Mans and from Angers to Nantes, A81 from Le Mans to Vitré, and A71 from Orléans to Bourges.

The evaluation of pavement structure conditions calls for a precise knowledge of the heavy traffic that has used it from the day it was put into service. For a toll highway network, it is relatively easy to know the volume of heavy traffic with the counting systems used for controlling toll receipts. However, this information does not usually determine whether the vehicle is loaded. Thus, the weight supported by the pavement remains unknown. Moreover, toll rates include in the same category different types of vehicles, the aggressiveness of which can be very different.

Many campaigns using WIM systems have been completed on the French national roads network. Nevertheless, nothing revealed the possible error in using the results of these campaigns to evaluate heavy traffic on the highways that were

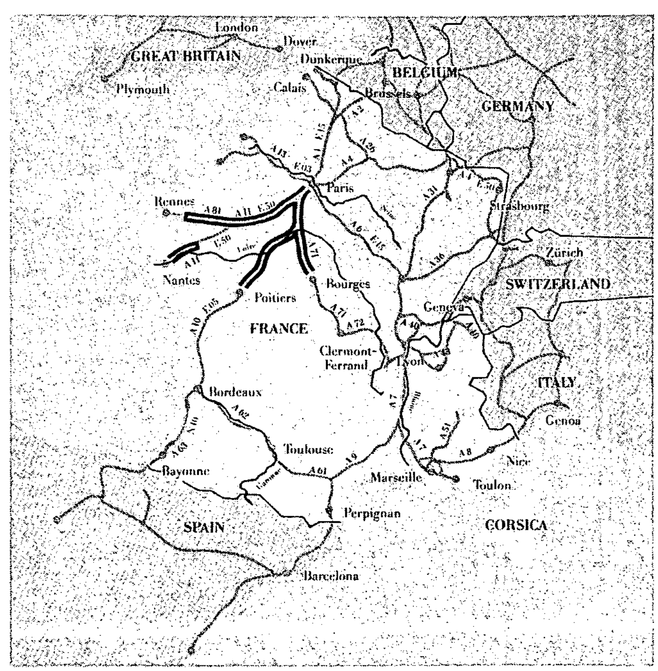

FIGURE 3 French and Cofiroute's motorway network.

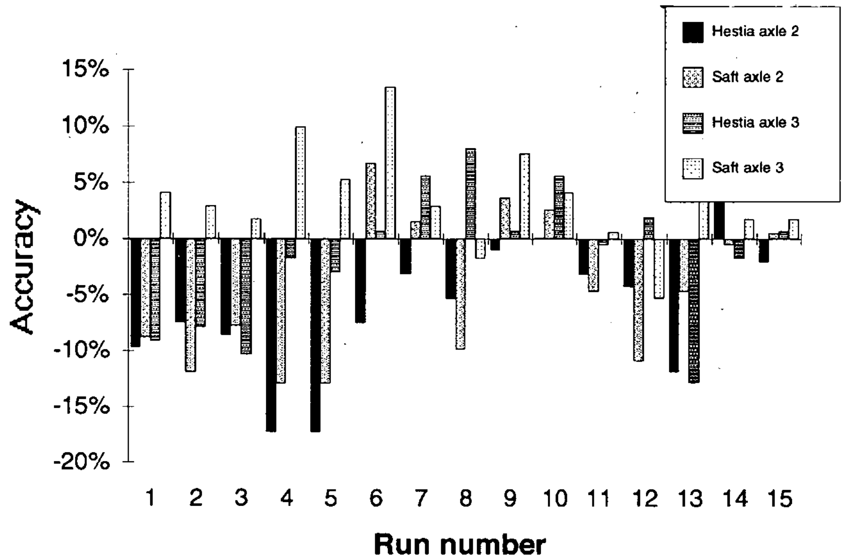

FIGURE 7 Double-axle weights on three-axle truck.

Last, axle spacing obtained by Hestia is excellent because it is often within a range of 5 ot 7 cm (2 or 3 in.) above or below statical value. The maximum recorded value is 9 cm (4 in.).

Additional Statistical Results Obtained with Hestia

Other experiments were performed on French highways in 1992. They gave additional results about accuracy on traffic flow and speed. A comparison with videotape recording of 3,000 vehicles showed a difference of less than 0.4 percent on traffic flow and less than 0.3 percent with a 22-category classification. A sample of 150 vehicles whose speed was previously measured by a standard radar gave 95 percent of speeds with an accuracy of 2 percent. No deviation was more than 3 percent, and accuracy was constant from 60 to 170 km/hr (37 to 110 mph).

Last, an experiment was made in July 1992 with three Hestia under the following conditions: (a) two sensors per station, (b) 30 m (98 ft) between each station, and (c) independent self-calibration for each station. The first results emphasize that multisensor weighing appears to improve accuracy and lessen deviation. To set an example, with only one sensor, maximum deviation was 13 percent for an axle and 8 percent for gross weight. With three pairs of sensors both maximum deviation and gross weight were reduced to 4 percent.

CONCLUSIONS

In addition to fulfilling the presented objectives and achieving the announced and expected devices, the goals of this project are to make WIM tools and their applications better known and to provide national technical and financial support to research and development actions (R&D). Consequently, customers are much better informed about new developments; they are associated with the R&D actions and support them. Their needs and demands are more seriously and more quickly considered during development. Manufacturers and suppliers also get substantial technical assistance from laboratories and the administration, which puts the road and highway networks and some technicians at their disposal for testing sensors and stations. Recent measurements obtained on a motorway network with a Hestia device have given satisfying results with respect to French recommendations for the acceptance of WIM stations. Similar results were obtained with a SAFT 2000. Therefore, France now has at its disposal two types of operational WIM station. By the end of 1992, Cofiroute, a private toll motorway company, had started the equipment of its network with two Hestia stations.

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cisely, it needed to know which results could be obtained with Cofiroute's own pavement and traffic.

Here accuracy consists of a set of criteria that includes bias, average, standard deviation, and statistical range of measurements. The axis of ordinates in the following figures gives (in percentage points) for each test run the following quantity:

$$\frac{DW - SW}{SW}$$

where DW is dynamic weight and SW is statical weight.

On one of the company's best sites in terms of geometric and pavement characteristics, two pairs of sensors were placed 100 m (330 ft) from each other. In this manner complementary measurements could be performed as well with a SAFT 2000, another French device. The experiment lasted 2 days, and the two stations worked alternately on each site. Five test vehicles were used: three two-axle trucks, one three-axle truck, and one four-axle articulated truck. For reference purposes, statical weights are given in Table 4.

Statical axle spacing values, where d_{ij} is the distance between axle i and axle j, are shown in the following table:

Truck Number	d_{12} [*m*(*ft*)]	d_{23} [*m*(*ft*)]	d_{34} [*m*(*ft*)]
1	3.20 (10.50)		
2	2.74 (9)		
3	4.45 (14.6)		
4	4.00 (13.1)	1.35 (4.4)	
5	3.50 (11.5)	7.50 (24.6)	1.35 (4.4)

Results

The Hestia station was connected the night before the beginning of the experiment to self-calibrate. First, there were a few test runs to calibrate each station. The target value for self-calibration of Hestia was increased by 5.2 percent after these runs. No further calibration was made after the experiment had actually started. Final results discussed here come from the average of the two sensors for Hestia and from only one sensor for SAFT 2000. The first remark concerns the effect of Hestia's self-calibration algorithm on results (Figures 4 and 5). Accuracy was clearly getting better in the afternoon of Day 1 (Runs 7 and up). Besides, in a general way test runs of Day 2 give better results, particularly with the articulated truck, whose pattern is considered characteristic.

On Day 2, dynamic weights on single axles ranged from −6 to 16 percent with Hestia and from −15 to 11 percent with SAFT 2000 for the first axle of the three-axle truck; results were similar for the articulated truck (Figure 6).

An analysis of the results given for each elementary axle composing a double axle shows that they are within the range of Category B, except for two values, with the three-axle truck (Figure 7). The two stations give results in Category C with the articulated truck.

Two things are worth noting: first, accuracy is almost always greater on the last axle, particularly for the articulated truck; second, better accuracy is obtained if a multiple-axle weight is globally considered.

TABLE 4 Statical Weights

truck n°	axle 1	axle 2	axle 3	axle 4	gross weight
1	1.25 [2700]	2.70 [5900]			3.95 [8700]
2	2.75 [6000]	3.05 [6700]			5.85 [12900]
3	5.35 [11800]	12.60 [27800]			17.90 [39400]
4	5.50 [12100]	9.65 [21300]	8.55 [18900]		23.85 [52600]
5	5.90 [13000]	12.80 [28200]	10.50 [23100]	8.25 [18200]	37.45 [82500]

Note: Weights are given in the thousands of kilograms (pounds in brackets).

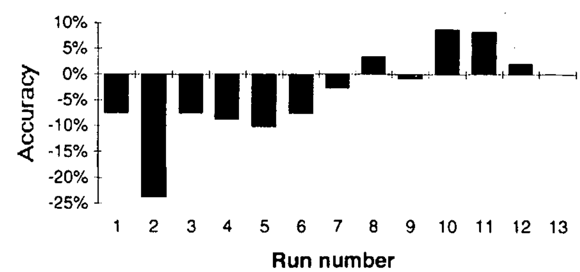

FIGURE 4 Effect of Hestia's self-calibration on accuracy, gross weight (Day 1), three-axle truck.

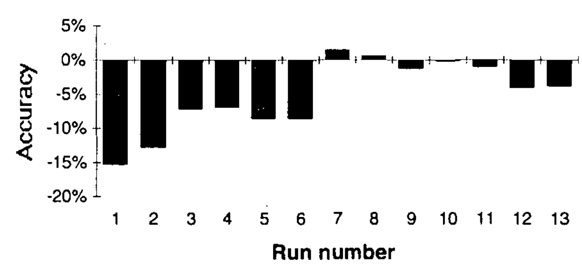

FIGURE 5 Effect of Hestia's self-calibration on accuracy, gross weight (Day 1), articulated truck.

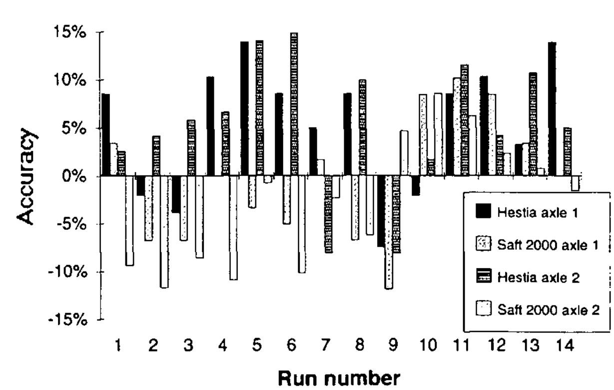

FIGURE 6 Dynamic single-axle weights for articulated truck.

TABLE 2 Choice of Operational Site

		Quality of site	
		Good	Fair
	Rutting (max. depth in mm)	< 5	< 10
Rigid and semi-	Average deflection (in hundredths of mm)	< 10	< 20
rigid pavement	Difference between axis and edge (in hundredths of mm)	+/- 3	+/- 10
Flexible	Average deflection (in hundredths of mm)	< 30	< 60
pavement	Difference between axis and edge (in hundredths of mm)	+/- 5	+/- 10
Evenness	Short waves	> 7	> 6
(in APL 72 marks)	Long waves	> 8	> 7

Acceptance of WIM Stations

Because the fundamental element most responsible for the accuracy of the results is the sensor-pavement pair, it is necessary to ensure that the sensors are well placed, both mechanically and electrically. In a general way, the authors refer to the recommendations for the placement of piezoelectric sensors, a guide published by the LCPC (*5*).

The calibration method followed is different for each category of station. For example, Category D involves checking vehicle flow, speed, and classification using a sample of 20 to 50 vehicles.

Other categories require a test method with one or many types of vehicles, for example:

- Category C: One truck with at least one multiple axle [a single axle of about 13 T (28,600 lb) and a double axle between 19 and 21 T (42,000 and 46,000 lb)];
- Category B: One truck with two or three axles, and one articulated truck with four or five axles [a single axle between 8 and 13 T (17,600 and 28,600 lb) and a double axle between 13 and 21 T (28,600 and 46,000 lb)].

First, each test vehicle is statically weighed: each axle must be weighed independently, then each axle group, and finally the whole truck. For multiple axles, all axles are simultaneously weighed; the operator must ensure that the sum of all axle weights is equal to the gross weight (within the accuracy of the weigh bridge used).

Second, each vehicle is run at a constant speed [between 40 and 90 km/hr (25 and 55 mph)] until 10 significant values are obtained. Tolerance is one value out of range for 10 significant measurements in Category C and for 20 in Category B.

Levels of tolerance concern the extreme values obtained. For weights, the reference is statical weight. These levels are summarized for each data item in Table 3.

Concrete Example: Results in Mer (July 1992)

Purpose and Conditions of Experiment

Before Cofiroute invests in a couple of WIM stations, the company wanted to test and evaluate the new Hestia according to the methodology described in this paper. More pre-

TABLE 3 Levels of Tolerance in Statical Weight for Categories B through D

	For every significant run		
data	Cat. B	Cat. C	Cat. D
traffic flow per pattern	+/- 3%	+/- 5%	+/- 10%
traffic flow	+/- 1%	+/- 3%	+/- 5%
speed	+/- 4%	+/- 6%	> 6 %
axle-spacing	+/- 10 cm [0.3 ft]	+/- 30 cm [1 ft]	+/- 50 cm [1.6 ft]
single axle weight	+/- 10%	+/- 15%	> 15 %
multiple axle weight	+/- 10%	+/- 15%	> 15 %
elementary weight of each axle composing a multiple axle	+/- 15%	+/- 20%	> 20 %
gross weight	+/- 10%	+/- 15%	+/- 30%

being managed. Some considerations could even challenge such a hypothesis. For example, the proportion of long-distance traffic on highways will certainly involve a large number of trucks from countries where the legal axle load is lower than that in France (130 kN). Because of this, it was decided in the beginning of the 1980s to determine as exactly as possible and to follow up over a period of time the aggressiveness of heavy traffic. Only specific instrumentation makes it possible.

Equipment of Cofiroute's Network

Using data from toll statistics, the network managed by Cofiroute was first divided into sections of homogeneous truck traffic. Therefore it was possible to localize a limited number of traffic sensors on each of these sections.

Because the cost of continuous measurements on each section were too high in 1981, it was necessary to determine a reliable sampling method for measurement campaigns. The analysis of toll statistics showed the optimum duration of on-site real traffic measurement campaigns and the best time of year. Systematic studies comparing toll statistics with the results of these campaigns are being completed. These studies will determine the values of aggressiveness coefficients applicable to each class of vehicles in the toll tariffing system, thus making it possible to know the number of equivalent standard axles independently of the toll statistics on each highway section of homogeneous traffic.

WIM Station Evolution

SAFT 16 (Station d'Analyse Fine du Trafic) was developed 12 years ago for research needs, but it was decided that it would be used for operational measurements on this network. Since then, other equipment has been developed in France, such as the SATL in 1983 [Station d'Analyse du Trafic Lourd (Heavy Traffic Analysis Station)], which can collect and store accumulated data for each type of axle load (single, tandem, and triple axles). Recently a second generation of stations has appeared, one that uses new electronics and computing devices, such as Hestia and SAFT 2000.

In 1992, a couple of new stations were used; they were more efficient than the old ones in the following ways:

- Greater accuracy in the whole range of axle load (from 10 to 150 kN);
- Bigger data storage capacity on the site;
- Less electrical consumption; and
- Greater ability to record traffic data (up to eight lanes).

These new stations are permanently installed on a highway section and linked through a communication network to the local maintenance center. These first devices will be quickly followed by others, as the highway network is equipped with a traffic management system. Most of these traffic stations will be able to distinguish only cars and trucks; calculate traffic flow, speed, occupancy rate, and so on; and send the aforementioned data to the maintenance center every 6 min. About 10 of them will be able to collect detailed axle loads and spacings, vehicle by vehicle (using piezoelectric sensors).

Evaluation of Needs and Acceptance of WIM Stations

Let us call a WIM station the piezoelectric sensors and the electronic system that analyzes the signal. Depending on the nature of the needs, the authors have adopted the methodology concerning the choice of a site and the acceptance of such a station, described previously (*6*). This methodology was defined in cooperation with the LCPC and the other WIM project members.

Choice of Operational Site

The needs can be summarized in the three points that follow, in order of increasing accuracy. Each corresponds to a category of WIM station:

- Category D: To have a basic idea of weights to classify vehicles using their load,
- Category C: To build histograms of loads, and
- Category B: To determine as exactly as possible each axle load or multiple-axle load and the gross weight.

(Category A would concern future stations with a higher level of accuracy.)

The choice of a site is closely bound to the purpose of the measurement (*7*). In view of these needs, the authors determine three classes of sites (fair, good, excellent) satisfying some geometric criteria and pavement characteristics (rutting, average deflection, and evenness). This evaluation is made from 200 m before the placing of sensors to 50 m behind.

Geometric criteria are the same for every class of site:

- Longitudinal gradient less than 2 percent, with no break in the slope,
- Cross-fall less than 3 percent, and
- Radius of curvature greater than 1000 m (3,300 ft), but a straight line is preferred.

Pavement characteristics such as evenness and cracks may affect the accuracy of the results. In addition, deflection and rutting have an impact on both the reliability and the life of the sensors.

Concerning deflection, the level of tolerance depends on the type of pavement, as given in Table 2 (10 mm = 0.39 in.). The following are noteworthy:

- The profilometer APL 72 gives a mark every 200 m (660 ft), ranging from 1 to 10 (10 means excellent); it is then necessary to determine more precisely the area in which the sensors should be placed to avoid a particular point (*8*).
- Deflection is measured every 20 m by measurements in the axis and the edge of the pavement; only the greater of the two values is kept, and then the average is calculated every 200 m.

A good balance between site and station is important too: even with a station in Category B, accuracy cannot be guaranteed on a fair site. On the other hand, it is useless to require a good site for a station in Category D.