Spatial Repeatability Of The Impact Forces On A Pavement And Multiple Sensor WIM—Research Element 5 Of The OECD IR6 DIVINE Project

Repetabilite Spatiale Des Forces D'Impact Sur Une Chaussee Et Pesage Multicapteur—Project OCDE IR6 DEVINE, Element 5

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ABSTRACT

The OECD's DIVINE road research project (1993-95) includes six complementary elements. Element 5, in which the TRL (UK) and the LCPC (F) are participating, consists of studying the spatial repeatability and variations of axle impact forces along a pavement, versus its evenness and the characteristics of the vehicles, including their suspensions. The TRL has conducted an experiment on the Abington motorway site (1991-94). The LCPC began an experiment in 1994 on the RN10 (Trappes). The site was instrumented with 18 bars and 3 weigh-in-motion stations. Calibration operations and preliminary measurements have been performed, using in particular a Canadian instrumented vehicle (NRC).

PRESENTATION OF THE DIVINE PROJECT

OBJECTIVES AND ORGANIZATION

DIVINE (Dynamic Interaction between Vehicles and INfrastructures Experiment) is a road research project of the OECD (Organization for Economic Co-operation and Development) aimed at adding to our knowledge of the aggressiveness of heavy goods vehicles HGV) on pavements and identifying means of limiting it so as to reduce the costs of road maintenance [1]. The dynamic effects due to the interaction between evenness and vehicles lead to increases in the local stresses in the pavements and bridges with respect to the effects of the static loads of the same vehicles, and therefore to reductions of the lives of these structures.

Furthermore, road transport has for several years been the principal goods transport mode. It accounts for a large volume of business and is an essential part of world economic activity. The carriers are exerting growing pressure to increase the loads allowed and therefore reduce their costs. At the same time, the managers of road networks, generally States or other governments, sometimes concessionnary operating companies, are attempting to reduce their maintenance costs, which are paid in the end by the community. One way to reconcile these concerns, which are contradictory but contribute to a global increase of wealth, is to reduce dynamic surcharges by using "soft" suspensions. Truck builders can also benefit from this development.

Theoretical economic estimates in the billions of dollars have been advanced for the potential reduction of road maintenance costs in OECD countries through a reduction of these dynamic surcharges and the introduction of "soft" suspensions. The DIVINE project proposes checking the assumptions underlying these estimates and validating the relevance of the solution being considered, primarily through experiments.

DIVINE, with a budget of more than a million dollars (and at least as much in contributions in kind) provided by OECD member countries and industrial partners, is divided into six research elements implemented by about ten public and para-public organizations. The project began in 1993 and is due to October 1996. The six elements are:

1. Accelerated test of damage of pavement(s) on the CAPTIF circular fatigue test track of Christchurch, New Zealand, comparing the effects of two types of suspension, spring (steel) and air ("soft");
2. Analysis of the primary responses of different pavement structures under the effects of vehicles and axles with both types of suspension, as a function of weights, silhouettes, and speeds;
3. Identification of the dynamic parameters of heavy vehicles on vibration benches, as a function of their suspensions;
4. Numerical modelling of vehicles and of their dynamic interactions with pavements;
5. Analysis of the spatial repeatability of axle impact forces on pavements versus evenness and vehicle characteristics;
6. Study of dynamic interactions between vehicles and bridges.

The LCPC (France) and the TRL (Great Britain) are contributing mainly to the implementation of research on element 5. The project as a whole is being followed by the OECD's IR6 group of experts.

DESCRIPTION OF ELEMENT 5

This is based essentially on the instrumentation of sections of pavements using weigh-in-motion sensors that measure the forces of impact of axles as they pass over various sections. The aim is to analyze the variations of these forces of impact along the pavement, in amplitude, frequency, or wavelength, detect any spatial repeatability, and correlate it with the evenness profile. These variations naturally depend on the dynamic characteristics of the vehicles and their type of suspension, but may also depend on their speeds, silhouettes, weights, etc.

An attempt is made to detect and quantify any reductions of amplitude of these variations by "soft" suspensions, according to the type of vehicle and, possibly, its load condition and the traffic. An attempt is also made to identify the evenness defects that cause the largest and therefore most harmful systematic surcharges. In addition to these expected benefits to pavements, these tests will make it possible to advance in the specification and development of multiple-sensor weighing systems optimized in terms of cost and effectiveness to measure the true weight of axles and trucks under normal traffic conditions. Such systems will have particular applications in the control of surcharges, and even in commercial weighing.

BRITISH EXPERIMENT (TRL)

The TRL had as early as 1991 undertaken theoretical and experimental researches, jointly with the University of Cambridge, on the spatial repeatability of axle impact forces and multiple-sensor weighing [2]. An experiment was begun on the A34 motorway near Abington in September 1991, where 16 capacitive weighing sensors [3] were made and installed by Golden River on the slow lane of the South-North direction, near a static weighing area. Each of these sensors, 1.8 m long, measures the force of impact of a half-axle; they are installed in pairs to allow localized measurement of the force of impact of axles. The evenness of the instrumented pavement section was mediocre at the start, and the pavement was resurfaced in November 1992. The site was completed in February and March 1993 to reach 48 sensors, or 24 measurements lines evenly spaced 2.70 m apart [4]. Golden River also provided the weighing stations associated with these sensors (Marksman 600).

After a few months of adjustments, the sensors were calibrated in June 1992 using an instrumented 32-t truck (4-axle semi) belonging to the TRL. It measures, at a frequency of 100 Hz, the forces of impact of wheels. From these measurements and the responses of the sensors, calibration coefficients between 0.28 and 0.62 have been established (cf. procedure described below). The system then recorded the forces of impact of at least 4000 axles exceeding 5 t and a similar number of vehicle "dynamic weights", at a mean speed of 86.5 kph; some were also weighed in static mode on the nearby area. This body of results has been analyzed by Barbour [5] at the TRL. The analysis concerns variations of an impact factor, defined as the ratio of the impact force measured on a sensor to the static weight (or estimate thereof from the mean of the impact forces on all of the sensors). This mean impact factor for a large number of wheels exhibits variations of the order of ± 20 % (fig. 1). The spatial repeatability of this impact factor has been determined and seems to persist over time, with a slight increase of its amplitude at some points. On some sensors the impact factor increases slightly with speed; on the other hand, it most often remains stable when the static weight of the wheel varies. More detailed analyses have been done as a function of the silhouettes of the trucks.

A more complete description of this experiment and of the latest results is given in [6].

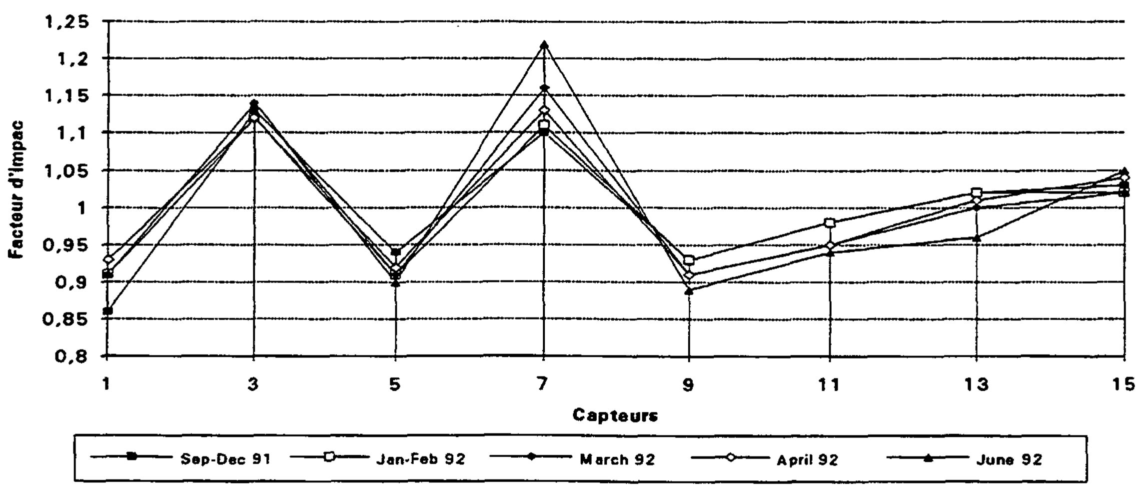

Figure 1. Impact factors at the Abington site (GB), from [4]

INSTRUMENTATION OF THE FRENCH SITE (RN10)

CHOICE AND CHARACTERISTICS OF THE SITE

The site was chosen according to several criteria:

- road with high traffic, with a large proportion of trucks (HGV): 2x2 lanes, 30,000 vehicles/day, 25 % of them HGV. While it is in a peri-urban zone, the expressway character of the road nearly always allows a smooth flow of traffic at a steady speed;
- conditions of accessibility and safety: RN10 at La Verrière (78), near Trappes, 35 km from Paris, near the LROP (Regional Laboratory of Western Paris Area). The pavement is divided by a central island and flanked by usable shoulders with safety fences. There are also two lanes for local traffic on the sides;
- other facilities: there is a static weighing area on the RN10, approximately 2 km upstream of the site, allowing weighing of vehicles from the traffic. There was already a concrete shelter connected to power and telephone networks. Given the access ramps and the adjacent local roads, the duration of rotation of vehicles on the site is approximately 10 min;
- qualities of pavement: mixed structure including 50 cm of cement-bound materials, 15 to 18 cm of bitumen-bound materials, and 8 cm of bituminous concrete. The characteristic deflection ($m+2\sigma$) is less than 0.15 mm, and the evenness is rather good, with APL (Analyseur de Profil en Long) ratings of 7, 7, and 6 in the small, medium, and long wavelength ranges.

INSTRUMENTATION OF SITE

Following a national call for tender, on the basis of a detailed specification, the LCPC in March 1994 finally selected several suppliers:

- Thermocoax supplied eighteen class 1 piezo-ceramic cables 3.20 m long with connecting cables. These were coated to form weighing bars, using the new technique of CETE Normandie [7], by Transfibre. These bars have been tested in the laboratory by the LROP following an approved procedure [8], then on the road [9].
- From 2 to 4 May 1994, Drouard installed 18 bars and 3 magnetic loops on the slow lane in the provinces-Paris direction, together with all underground connections up to the nearby shelter (fig. 2).
- These bars were placed in a grid (fig. 3) at non-uniform distances: 7 bars 0.375 m apart, then 4 bars 1.125 m apart, and finally 7 bars 2.25 m apart. The total length of the grid is thus 22.5 m. This configuration satisfies several signal frequency sampling criteria (force of impact).
- Vectra supplied 3 SAFT2000 weigh-in-motion stations, made by LEEM, two of them on loan for the duration of the DIVINE project. Each of these stations can manage 8 weighing bars and is connected to a loop. It records the instants of passage of axles, the speeds, lengths, and types of vehicles (according to silhouette), and the force of impact of each axle and the cumulative total weight, by bar. These stations were installed on 9 May.

CALIBRATION OF MEASUREMENT SYSTEM

Calibration of the measurement system is essential, given the aim pursued. It is essential that each bar measure, as exactly as possible, the impact force of the axles, and not their weight, as one generally tries to do in weigh-in-motion operations. The aim is therefore not to eliminate the effects of evenness on the axles, since these effects are just what is to be studied. Procedures for automatic calibration of the stations using traffic constants therefore had to be set aside, and other approaches found.

INITIAL CALIBRATION USING PRE-WEIGHED TRUCKS

As soon as the stations were received, a pre-calibration was conducted to centre the response of each bar on the static weight. This was done to eliminate the large bias arising from the sensitivity and conditions of installation of the bars. Two vehicles pre-weighed in the static mode (a 2-axle deflectograph and a T2R3, a 2-axle tractor with a semi-trailer with tridem axle), each made 12 passes at three speeds (40, 60, and 80 kph). This established initial calibration coefficients (CI_i) for each bar i (table 1). Their mean, CI, is 0.65. Figure 4 contains the values of these coefficients, recentered on 1: CI_i/CI.

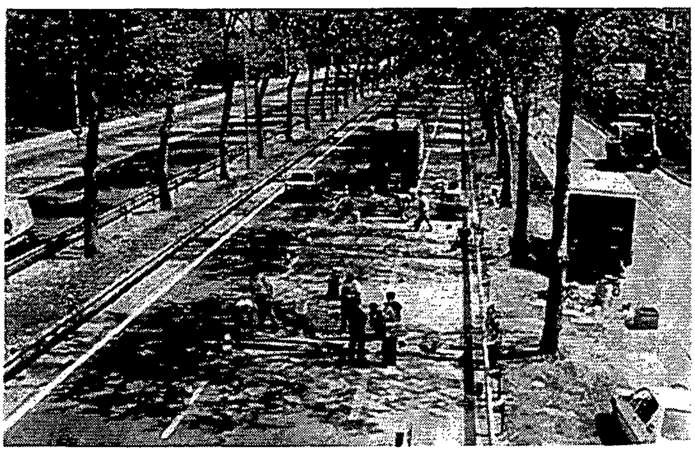

Figure 2. Installation of bars on RN10 site

Figure 3. View of instrumented RN10

Bar	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
CIi	.67	.75	.69	.67	.65	.60	.64	.60	.58	.59	.59	.57	.61	.66	.77	.75	.60	.80

Table 1. Initial calibration coefficients

CALIBRATION USING SPECIFIC DEVICES

Two calibration systems performing a calibration on impact forces and not on static weights were used. They create repetitive localized excitation on the bars:

- the FWD (Falling Weight Deflectometer) applies a calibrated impact on a circular imprint 30 cm in diameter;
- the ®Piézodyn, a prototype developed by LEEM to test cables and bars in the laboratory, applies a calibrated sinusoidal force to the sensor; the mean of the response of the sensor over several periods is then used. This apparatus was installed at the site and used for the first time on bars installed in the pavement (5 x 11 cm imprint).

These measurements were made between 16 and 27 May 1994. For each system, four imprints per bar were tested, three of them around the mean right wheel path of the vehicles and one centered on the left wheel path (for practical reasons - size - it was not possible to go further left on the pavement). A weighted mean of individual measurements for each bar was selected, with weighting coefficients of 2/9, 2/9, 2/9, and 1/3, to partially correct for the right-left difference in number of measurements. The individual measurements of these two devices on the same bar are highly scattered (even more for the FWD than for the ®Piézodyn), with deviations of up to 30 to 50 % for a single bar. This is in all likelihood due to the bearing conditions and to local pavement evenness. The mean result is therefore relatively imprecise.

For each bar i, from the mean measurement selected x_i, a coefficient of calibration, dimensionless and centered on 1, was calculated using the formula:

$$C_i = \frac{\sum_{j=1}^{18} x_j}{18.x_i} = \frac{\bar{x}}{x_i}$$

In effect, the more sensitive the bar, the higher the x_i (responses of the bars to the calibrated impact, in mV). Coefficient C_i is therefore inversely proportional to x_i. These coefficients, C_{piez} and C_{fwd}, are shown in figure 5. The final operational calibration coefficient, derived from these methods, that should be selected would be $C'_i = C_i.CI$, to yield results centered on the static weight.

CALIBRATION USING AN INSTRUMENTED HGV

In the context of the DIVINE project, the Canadian National Research Council (NRC) sent to Europe an instrumented heavy vehicle [10] capable of continuously measuring (with a sampling frequency of 500 Hz) the forces of impact of its wheels, with a stated precision of 3 % [11] (fig. 4). This vehicle is a 3-axle (one tandem) tractor, with a tandem semi-trailer additionally fitted with a liftable intermediate axle, carrying a tank with 4 compartments. The vehicle, of which the suspensions are interchangeable, was fitted in France with air suspensions. Between 1 and 6 June 1994, it made 91 passes on the RN10 site, in 5 load configurations and at 3 speeds, as per the plan summed up in table 2.

The forces of impact were measured over a distance of 80 m, including the weighing grid, in steps of 1.67 cm to 4.44 cm (depending on speed). Thanks to an identification system and synchronization, it was possible to calculate, for each wheel, then for each axle (sum of two wheels), the force of impact at the bars, by interpolation between the values on either side. The force-of-impact signals were filtered by a 45-Hz low-pass filter to eliminate noise and remote harmonics, since the highest natural frequencies of HGV or pavements do not exceed 25 Hz. Then a total apparent "dynamic" weight PD was calculated for each bar and each pass, by adding the forces of impact of all axles (measured by the HGV at different times!). P'D is the "dynamic" weight of the HGV calculated for the same pass, for each bar, by adding up the responses of the bar for each axle. The calibration coefficient selected for a bar i, CF_i, is equal to the mean (for all passes of the HGV) of the values of PD/P'D (table 3). Figure 5 gives the values recentered on 1: CF_i/CF (where CF is the mean of the 18 values CF_i).

It will be noted that similar calculations were done to determine calibration coefficients directly from the forces of impact of single axles, tandems, and all axles, and that the results differ no more than 3% (precision of the measurement system) from those presented.

Date	1/6	2/6	2/6	3/6	3/6	6/6
TLW (T)	24	35.9	36.4	44.25	44.45	17.39
Nbr. axles	5	5	6	5	6	5
Passes	4 - 3 - 3	3 - 3 - 3	3 - 3 - 3	6 - 6 - 6	9 - 9 - 9	6 - 6 - 6

Table 2. Plan of measurements of instrumented HGV (the passes are at 80, 50, and 30 kph)

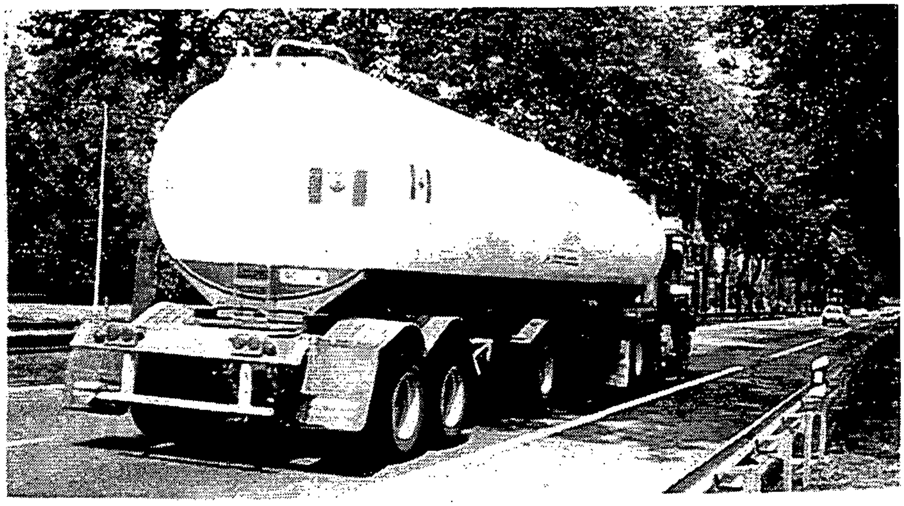

Figure 4. Canadian instrumented heavy vehicle of the National Research Council (NRC)

Bar	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
CF_i	.64	.70	.65	.66	.65	.59	.62	.59	.59	.59	.60	.59	.57	.64	.75	.76	.74	.95

Table 3. Calibration coefficients derived from the Canadian instrumented HGV

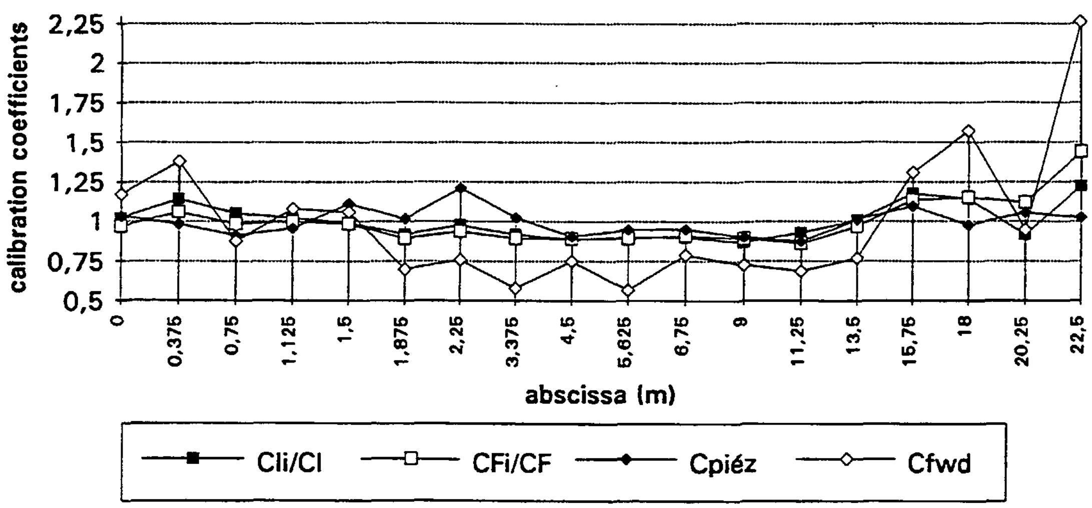

Figure 5. Calibration coefficients centered on 1, for each bar, by the various methods

EVALUATION OF CALIBRATION METHODS AND CONCLUSIONS

We finally selected the coefficients CF_i for the calibration of the bars, given the precision of measurement of the forces of impact by the instrumented HGV; this method is taken as reference for the evaluation of the others. Concerning the other three calibration methods, it will be noted here:

- that the initial method, consisting of having two trucks of known weight travel on the surface, gave the results closest to the reference, with deviations between +7 % and -3.5 % for each bar, except the last two (17 and 18) where -18.9 % and -15.8 % were reached. This method, used traditionally for the calibration of weighing bars when automatic calibration is not available, is best when the evenness is good, as is the case here (APL ratings of 7 in the grid zone);
- that, of the two methods using impact or pressure apparatus, the ®Piézodyn gave results that were clearly better than those of the FWD, but still rather different

from the reference: the deviations are less than ± 15%, except for bars 17 and 18 (± 28.8 %). However, it will be noted in figure 4 that the variations of coefficients C_{piez} and CF_i are rather well correlated along the pavement, except for values 17 and 18. It would therefore seem that this method could be improved (in particular by slightly increasing the number of measurement points per bar and by optimizing the impact imprint) to allow operational calibration. Its technical and economical advantages with respect to the first method must still be studied. It saves travel by pre-weighed vehicles (but requires a counterweight vehicle) and is independent of evenness, but the lane must be closed for several hours.

- finally, that the coefficients deduced from the FWD exhibit deviations of up to more than 35 % from the reference, and even nearly 57 % on bar 18. Given the intrinsic dispersion of the individual measurements of this method and the low correlation with the reference, it must be judged totally unsuited to the calibration of weighing bars.

These first analyses, confirmed by the study of variations of impact forces measured by the instrumented HGV, already indicate that the latter are of rather low amplitude (approximately 10 to 15 %).

FIRST RESULTS AND PROSPECTS

At the current stage of the measurements and their analysis, it is still too early to present definitive results, much less conclusions. However, we may say a few words about the first results already produced outside of the calibration.

ANALYSIS OF IMPACT FORCES OF INSTRUMENTED HGV

The analyses concerned first the general statistics of the impact force values of wheels and of axles, in terms of mean, standard deviation, minima and maxima, by pass, then by set of passes at the same speed and/or in the same load configuration (and number of axles). The standard deviations by wheel are nearly 0.1 t (or a mean coefficient of variation of 5 %), and the largest min-max spans of the order of 1 t (or ± 20% with respect to the mean). The standard deviations by axle are naturally less, insofar as there are phase differences between the right and left wheels: the relative error of impact forces reaches 5 to 10%, depending on the axles, between one wheel and the mean of both wheels. The impact forces by axle are still ± 10% of the static weight, except for axle no. 4 (liftable), for which the range of deviations is from 0 % to +20 %. These impact forces are only slightly scattered for this vehicle with a "soft" suspension on a surface of good evenness.

The study of the spatial repeatability of the impact forces for this HGV shows, in a first analysis:

- a good repeatability by wheel, for the same load configuration and same speed; this repeatability remains when the load varies: the absolute value of the variations of impact force remains around 0.7 t, independently of the static weight;
- the spatial repeatability is lost when the speed varies; this is explained a priori (cf. below) by the fact that on a good evenness, the vibrations of the HGV itself caused by a small local defect prevail over the effects of the evenness up to the next defect. A frequency repeatability, rather than a spatial repeatability, is therefore to be expected;
- finally, the total "local dynamic" weight, obtained by summation of the impact forces of all wheels at the same point, exhibits variations of 10 to 15 %, increasing with speed.

A spectral study (in frequency and wavelength) of these impact forces was conducted using a fast Fourier transform (FFT) with Hanning windows to correct for non-periodicity effects. The main results for wheels and axles are:

- the natural frequencies, apparently linked to the vehicle, that emerge in the spectrum are located at 1.5-1.65 Hz, then 3.1 Hz (especially for the two front wheels), then around 8.5 Hz and 11.4 Hz. These frequency peaks seem nearly independent of speed. The second peak might be a cab frequency or a harmonic of the first ?
- several wavelengths emerge in the spectrum and are found at all speeds: around 9 m, 3.28 m, 1.64 m, 1.08 m, 0.8 m, 0.64m, 0.54 m, 0.46 m, 0.4 m, 0.32 m. The one at 3.28 m might be related to the wheel circumference, with the one at 1.64 m deriving from a harmonic. Below 1 m, what is found would mostly be an effect of macrotexture. In addition, at the speeds of 30 and 50 kph, a wavelength at 50 m is found (and 37 m at 80 kph).

These results are only slightly influenced by the load configuration of the vehicle. A look at the phase differences between the right and left wheels of a given axle shows phase oppositions for the 50-m wavelengths and independence of phases for the wavelengths of 1.64 m, 0.54 m, and 0.32 m. This seems to be a matter of evenness effects, with a roll effect at low frequency (below 0.6 Hz, and a function of speed), and differences of evenness between the right and left wheel paths for the other wavelengths (short or macrotexture). On the other hand, at the other frequencies (or wavelengths), there is phase equivalence.

For the total "local dynamic" weight, what is found is basically the frequency peaks (of the body) at 1.5-1.65 Hz (and the harmonic at 3.1 Hz ?) and certain wavelengths such as 0.54 m. On the other hand, the peak at the wavelength of 3.28 m disappears, together with the one at 50 m, because of the phase differences between axles and because of yaw.

CONTINUATION OF STUDY

Beyond these first analyses with a particular HGV, a large-scale measurement programme has been started, with vehicles taken from the traffic and pre-weighed in static mode at the area upstream of the site (a few tens of HGV per month). Insofar as possible, the type of suspension of these vehicles is identified during the static weighing with a view to distinguishing the different behaviours according to suspension type. Finally, a few tens of thousands of HGV from the traffic will also be recorded, using as "static" reference an estimate based on the mean of the values from the different bars, and the relative error will be calculated for each bar. This will make it possible to compare the effects of evenness for different types of vehicles, silhouettes, and suspensions.

Software tools are being developed to automate the statistical analysis of the results as much as possible. Many measurement files have already been recorded, including either pre-weighed vehicles or vehicles from the traffic, since September 1994.

Final, studies will be continued after the DIVINE project to use the knowledge acquired to improve weigh-in-motion systems and specify an optimized multiple-sensor weighing system.

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